

**DECENTRALIZED CONTROL TECHNIQUES
FOR DISTRIBUTED AIR/GROUND
TRAFFIC SEPARATION**

Jimmy Krozel, Ph.D., and Mark Peters

Prepared for:
NASA Ames Research Center
Moffett Field, CA 94035

Submitted by:



SEAGULL TECHNOLOGY, INC.
16400 Lark Ave., Suite 100
Los Gatos, CA 95032-2547

Prepared under contract to:
System Resources Corporation, A Titan Company
700 Technology Park Drive
Billerica, MA 01821-4134

TASK ORDER: RTO-36, 1266-140
Under NASA Contract NAS2-98005

June, 2000

ACKNOWLEDGMENTS

This research was funded by NASA Ames Research Center under contract NAS2-98005 for the Advanced Air Transportation Technologies (AATT) program. The authors appreciate the program support and active research participation of Dr. Karl Bilimoria at NASA Ames Research Center, Moffett Field, CA. We also appreciate the supporting investigations in centralized control from Prof. J.S.B. Mitchell at the State University of New York (SUNY) Stony Brook.

ABOUT THE AUTHORS



Jimmy Krozel, Senior Engineer (Ph.D., Aeronautical and Astronautical Engineering, Purdue University, 1992). Since joining Seagull Technology in Aug., 1995, Dr. Krozel has worked on aircraft conflict detection and resolution for Free Flight, the database management of aircraft, terrain, and navigation aid data, collaborative decision making, aircraft terminal area routing around heavy weather, and intent inference for aircraft. His research interests are in the areas of advanced visualization systems, air traffic control, air traffic management, Free Flight, route planning, autonomous vehicles, and intelligent path prediction. Dr. Krozel performed his M.S. thesis research under a fellowship at the NASA Ames Research Center, and performed his Ph.D. thesis as a Hughes Doctoral Fellow at the Hughes Research Laboratory. Dr. Krozel is a member of the American Institute of Aeronautics and Astronautics (AIAA), American Association for Artificial Intelligence, Tau Beta Pi, Sigma Xi, and Sigma Gamma Rho. Dr. Krozel has a total of 20 technical publications, with two publications receiving “Best Paper” Awards at AIAA conferences. Dr. Krozel is on the editorial board of *Applied Intelligence*, Kluwer Academic Publishers.



Mark E. Peters, Project Engineer (M.S., Aeronautical and Astronautical Engineering, Purdue University, 1996) Mr. Peters joined Seagull Technology in June, 1996. He has interests in conflict detection and resolution for Free Flight, unmanned aerial vehicles, aircraft design, aircraft stability and control, and flight mechanics. Mr. Peters has designed and built 5 unmanned air vehicles, and has co-authored 3 technical papers. Mr. Peters is a member of the American Institute of Aeronautics and Astronautics, the Experimental Aircraft Association, the Aircraft Owners and Pilots Association, and the Academy of Model Aeronautics.

TABLE OF CONTENTS

1. INTRODUCTION.....	1
1.1 Technical Issues Being Addressed.....	1
1.2 Engineering Approach.....	3
1.3 Technical Report Organization.....	4
2. LITERATURE REVIEW	5
2.1 Hierarchical Control Systems.....	6
2.2 Distributed Control Systems.....	9
2.3 Hybrid Control Systems.....	13
2.4 Control by Permission, Periodic, and Supervisory Control Systems.....	14
2.5 Collaborative Decision Making Control Systems.....	16
2.6 Game Theory and Principled Negotiation Systems.....	18
2.7 Behavior-Based or Schema-Based Control Systems.....	21
2.8 Neural Network Control Systems.....	24
2.9 Fuzzy Logic Control Systems.....	28
2.10 Expert and Rule-Based Control Systems.....	31
2.11 Airspace Complexity, Dynamic Density, and Chaos.....	33
2.12 Alerting Logic.....	36
3. TRADE-OFF STUDY.....	41
3.1 DAG TS Functional Design Requirements.....	41
3.2 Trade-Off Features.....	41
3.3 Down-Select.....	44
4. DAG TS MODELING AND EVALUATION METHODOLOGY.....	45
4.1 System Performance	45
4.2 System Stability.....	52
5. IMPLEMENTATION AND DEMONSTRATION.....	55
5.1 Lateral Directional Dynamics.....	55
5.2 Lateral Guidance System.....	58
5.3 Communications.....	64
5.4 Scenario Generation.....	64

(continued)

TABLE OF CONTENTS

(Continued)

6. SIMULATION RESULTS	65
6.1 Low Density	65
6.2 Medium Density.....	71
6.3 Medium/High Density.....	76
6.4 High Density.....	81
6.5 Comparison of Results.....	87
7. CONCLUSIONS AND RECOMMENDATIONS	91
6.1 Conclusions	91
6.2 Recommendations.....	92
8. REFERENCES	93

ABSTRACT

The Distributed Air/Ground Traffic Management (DAG TM) concept allows for distributed decision-making for traffic separation and traffic flow management. In contrast to the current traffic management system which is a centralized, ground-based positive Air Traffic Control (ATC) system, DAG TM allows for an advanced Free Flight Air Traffic Management (ATM) concept that is a decentralized/distributed control system utilizing a triad of agents: the Flight Deck (FD), Air Traffic Service Provider (ATSP), and Airline Operational Control (AOC). In this report, we investigate the relationship between decentralized/distributed control mechanisms for traffic separation within DAG TM and the elements of system performance and stability as a function of dynamic density conditions. We review the literature in decentralized systems, distributed systems, hybrid systems, collaborative decision making, periodic control, principled negotiation, and other mechanisms for decentralized/distributed control. We then address the trade-offs between these potential mechanisms to identify the best approach for traffic separation in DAG TM. The approach is modeled and a simulation is constructed to demonstrate the benefits of a decentralized/distributed approach. Scenarios from Monte Carlo simulation studies are used to draw conclusions about decentralized control for traffic separation. In particular, we characterize the trade-offs between system stability and performance parameterized by dynamic density.

LIST OF ACRONYMS

2D.....	Two Dimensional
A/D.....	Analog/Digital
ADS-B	Automatic Dependent Surveillance – Broadcast
AOC.....	Airline Operational Control
ATCSCC.....	Air Traffic Control System Command Center
ATC.....	Air Traffic Control
ATM	Air Traffic Management
ATSP.....	Air Traffic Service Provider
CDM.....	Collaborative Decision Making
CE.....	Concept Element of DAG TM
CMAC.....	Cerebellar Model Articulation Controller
CTAS.....	Center-TRACON Automation System
D/A.....	Digital/Analog
DAG TM.....	Distributed Air Ground Traffic Management
DAG TS.....	Distributed Air Ground Traffic Separation
DOC.....	Direct Operating Cost
FAA.....	Federal Aviation Administration
FAST.....	Final Approach Spacing Tool
FD.....	Flight Deck
GA.....	General Aviation
GPS.....	Global Positioning System
IFR.....	Instrument Flight Rules
NAS.....	National Airspace System
NASA.....	National Aeronautics and Space Administration
RTCA.....	Radio Technical Commission for Aeronautics
SUA.....	Special Use Airspace
TFM.....	Traffic Flow Management
VFR.....	Visual Flight Rules

1.0 INTRODUCTION

This research effort investigates decentralized control techniques for distributed air ground traffic separation. In this Chapter, we review the technical issues being addressed, the technical approach of this work, and the report organization.

1.1 Technical Issues Being Addressed

1.1.1 DAG TM and DAG TS

The Distributed Air-Ground (DAG) Traffic Separation (TS) concept is a subset of a bigger DAG traffic management (TM) concept, which allows for distributed decision-making for traffic separation and traffic flow management. In contrast to the current traffic management system which is a centralized, ground-based positive Air Traffic Control (ATC) system, DAG traffic separation allows for an advanced Free Flight Air Traffic Management (ATM) concept that is a decentralized/distributed control system utilizing a triad of agents: the Flight Deck (FD), Air Traffic Service Provider (ATSP), and Airline Operational Control (AOC). Figure 1 illustrates the triad.



Figure 1. DAG TM is applicable to tasks performed by the triad formed by the Airline Operational Control (AOC), the aircraft Flight Deck (FD), and Air Traffic Management (ATM).

As shown in Table 1, the DAG TM paradigm has 15 Concept Elements (CEs) defined by NASA's DAG TM Team. As highlighted in this table, our research project contributes to CE 5 and CE 6. The desired solutions to CE 5 and CE 6 are as follows [DAG99]:

CE 5: *“Appropriately equipped aircraft accept the responsibility to maintain separation from other aircraft, while exercising the authority to freely maneuver in en route airspace in order to establish a new user-preferred trajectory that conforms to any active local traffic flow management constraints.”*

CE 6: *“Reduce unnecessary and/or excessive ATSP-issued route deviations for traffic separation by enhancing ATSP trajectory prediction capability through user-supplied data on key flight parameters. Facilitate trajectory change requests for en route aircraft by providing the user (FD and/or AOC) the capability to formulate a conflict-free user-preferred trajectory that conforms to any active local-TFM constraints.”*

Local Traffic Flow Management (TFM) constraints include hazardous weather, Special Use Airspace (SUA), airspace congestion, arrival metering/spacing. Further air carrier constraints include turbulence avoidance, terrain avoidance, and schedule constraints. Not all these constraints will be used in our research. We focus our research only on the cruise portion of the en route airspace, whereas the DAG TM concept elements 5 and 6 include departure, cruise, and arrival. In our work, we consider only conflicts between en route aircraft and do not consider hazardous weather, SUA, metering/spacing, turbulence avoidance, terrain avoidance, or schedule constraints.

Table 1. The DAG TM Concept Elements [DAG99].

C E	Flight Phase	Title
0	Gate-to-Gate:	Information Access/Exchange for Enhanced Decision Support
1	Pre-Flight Planning:	NAS-Constraint Considerations for Schedule/Flight Optimization
2	Surface Departure:	Intelligent Routing for Efficient Pushback Times and Taxi
3	Terminal Departure:	Free Maneuvering for User-Preferred Departures
4	Terminal Departure:	Trajectory Negotiation for User-Preferred Departures
5	En route: (Departure, Cruise, Arrival)	Free Maneuvering for: (a) User-preferred Separation Assurance, and (b) User-preferred Local TFM Conformance
6	En route: (Departure, Cruise, Arrival)	Trajectory Negotiation for: (a) User-preferred Separation Assurance, and (b) User-preferred Local TFM Conformance
7	En route: (Departure, Cruise, Arrival)	Collaboration for Mitigating Local TFM Constraints due to Weather, SUA and Complexity
8	En route / Terminal Arrival:	Collaboration for User-Preferred Arrival Metering
9	Terminal Arrival:	Free Maneuvering for Weather Avoidance
10	Terminal Arrival:	Trajectory Negotiation for Weather Avoidance
11	Terminal Arrival:	Self Spacing for Merging and In-Trail Separation
12	Terminal Arrival:	Trajectory Exchange for Merging and In-Trail Separation
13	Terminal Approach:	Airborne CD&R for Closely Spaced Approaches
14	Surface Arrival:	Intelligent Routing for Efficient Active-Runway Crossings and Ta

Within this DAG TM paradigm, user preferred trajectories can be planned to allow airlines to optimize their operations. Self-optimization is the objective rather than NAS system optimization. Thus, with no requirement for a centralized control system, a decentralized/distributed control system now becomes the focus of attention. However, distributed control may not be achievable within certain congested airspace because of conflicts between airline preferences, unpredictable weather, or other unforeseen problems. Such conflicts and, in general, the dynamics of decentralized control techniques, can impact system stability. The trade-off between the metrics of system efficiency and safety is important to monitor in such situations. In this report, existing principles and techniques for decentralized/distributed control are investigated to model the interaction between system performance and stability in a DAG TS paradigm of air traffic operations.

1.1.2 Trade-off between Performance and Safety

In our work, we investigate the trade-off between system performance and safety.

Performance is concerned with the evaluation of the efficiency of travel relative to user preferences. Air carriers generally establish on-time schedule as their primary performance metric since it is vital to establish connecting flights, crews, and other resources. In the pursuit of maintaining schedule integrity, user preferred trajectories are filed and updated as necessary. During the course of flight, efficiency measures include

- deviations from the nominal flight plan,
- on time performance meeting the next one or two waypoints in an intent broadcast,
- fuel usage, or
- other measures.

Thus, if users prefer to fly wind optimized routes, for instance, then any deviation from wind optimized routes that cause an increase in total direct operating cost affect efficiency. A measure of efficiency is defined in this research in Chapter 4.

Safety issues of concern to us for DAG TS are related to both conflicts and the potential for conflicts. We are primarily concerned with conflicts between aircraft, and not between aircraft and the ground or aircraft and hazardous weather or turbulence. A measure of safety related to conflicts between aircraft is defined in Chapter 4.

In this work, we are monitoring performance and safety relative to the airspace complexity as measured by dynamic density. We investigate the performance vs safety curves for low, medium, and high levels of dynamic density. A definition of dynamic density is formulated by reviewing the literature in Chapter 2 and a measure of dynamic density is defined in Chapter 4.

1.2 Engineering Approach

There are several objectives to this effort which constitute our engineering approach:

1. Literature Search. The first objective is to conduct a comprehensive literature search on existing decentralized/distributed control techniques and their engineering applications.
2. DAG TS Recommendation. The second objective is to recommend to NASA the most suitable technique (or combination of techniques) which appears to best solves the DAG TS problem.
3. Modeling and Evaluation Methodology. The third objective is to develop a methodology for modeling system performance and evaluating system stability for the chosen DAG traffic separation paradigm.
4. Implementation and Demonstration. The fourth objective is to implement, validate, and demonstrate the recommended DAG TS technique in a simple simulation of air traffic operations.
5. Coordination of Effort with NASA. Our work is well coordinated with NASA (including the NASA technical monitor, Dr. Karl Bilimoria, as well as other interested NASA personnel).

Because there is a limited amount of time in this research effort to perform a literature search, an “anytime algorithm”, defined as follows, is used for the engineering approach. The literature search topics are covered evenly and built up incrementally through the project. Thus, at anytime, the search can stop and the results can be summarized. In this way, more detailed information is added to the literature search as new information is discovered.

1.3 Technical Report Organization

This report is organized as follows:

- Chapter 1 introduces DAG TM and DAG TS problem for decentralized control,
- Chapter 2 provides a review of the literature for decentralized control techniques,
- Chapter 3 presents a trade-off study and a down select for decentralized control techniques,

- Chapter 4 discusses our modeling and evaluation methodology for system performance and stability,
- Chapter 5 presents the demonstration system for DAG TS concepts,
- Chapter 6 presents results based on the demonstration system software,
- Chapter 7 presents our conclusions and recommendations, and
- Chapter 8 presents references.

2.0 LITERATURE REVIEW

This chapter presents a literature review for decentralized control techniques for distributed air ground traffic separation. The literature review focuses on books, journal articles, and conference papers that are widely accessible in technical libraries. Magazine articles and obscure sources of material are not listed. Also, no World Wide Web pages are listed.

The literature review spans the topics:

Section	Topic
2.1.	Hierarchical Control Systems
2.2.	Distributed Control Systems
2.3.	Hybrid Control Systems
2.4.	Control by Permission, Periodic Coordination, and Supervisory Control
2.5.	Collaborative Decision Making Systems
2.6.	Game Theory and Principled Negotiation Systems
2.7.	Behavior-Based or Schema-Based Control Systems
2.8.	Neural Network Control Systems
2.9.	Fuzzy Logic Control Systems
2.10.	Expert and Rule Based Control Systems

A description of each of these control methods is provided first, and then a listing of the references associated with the topic is given with key words identified for each paper. The strengths and weaknesses of each method is highlighted in Chapter 3. Whenever possible, papers that describe ATM or ATC examples are noted. Additionally, whenever a topic has papers that specifically address the issue of stability, a note is made in the key words listing.

In addition, because the investigation of DAG TS involves the development of a methodology for modeling system performance and evaluating system stability, the following two topics are reviewed:

Section	Topic
2.11.	Airspace Complexity, Dynamic Density, and Chaos
2.12.	Alerting Logic

An extensive literature review of these two topics is not provided; however, sufficient review of the literature is included in order to establish the key aspects of these topics, as needed to perform this research project.

2.1 Hierarchical Control Systems

2.1.1 Theory of Hierarchical Control Systems

Hierarchical systems theory seeks to decompose a large scale problem into a multi-level hierarchical structure, according to the system characteristics. Special coordination procedures are then used to meet overall system objectives. To construct a multi-level system, the system is decomposed into a number of smaller parts which can be controlled locally in a straightforward manner. Then, a mechanism for coordination of all of the separate parts is created which achieves the goals of the overall system.

A hierarchy is a multi-level structure. For two systems A and B , the system A is the *supervisor* of system B if A has a direct causal influence on system B . The word *direct* means that the system A does not use an intermediate to influence the system B . The word *causal* means that the state of system B is dependent on the state of system A . System A is *superior* to system B when system A is the supervisor of system B , or system A is the supervisor of some system that is superior to system B . A system within a hierarchy that is not a supervisor is called a *terminal* system; thus, terminal systems are not superior systems. Formally, a *hierarchy* is a set of systems that satisfy the following criteria:

1. No system is superior to itself
2. One system in the set of systems is superior to all other systems in the set.

A hierarchy is *balanced* if every superior system is the supervisor of the same number of systems. A hierarchy is *overlapping* if there exists more than one supervisor for at least one system within the hierarchy. Figure 2 illustrates some general examples of hierarchical systems.

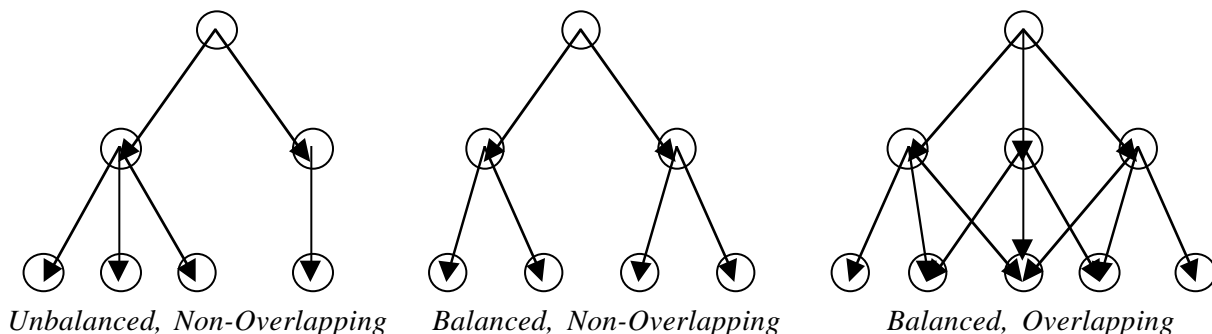


Figure 2. Example hierarchical systems.

Generally, there are three major classifications of hierarchical decomposition:

- Decomposition on the basis of structure
- Decomposition on the basis of levels of control, and
- Decomposition on the basis of levels of influence.

The inherent nature of the system to be controlled dictates which type of decomposition is warranted.

Decomposition on the basis of structure partitions the system into separate subsystems which have individual goals along with interaction within the system as a whole. The decomposition of the NAS into Class A, B, C, D, E, and G airspace is an example. Within each class of airspace, different local control laws apply; for instance, Class A airspace permits only IFR with ATC clearance requirements to pass into and Class G airspace permits IFR or VFR with no ATC clearance requirements. The local control is mostly a function of local measurements and local state variables. Most of this local information is not needed by the system as a whole. However, each discrete operation affects global variables, such as the rate at which aircraft move through a particular airspace. The coordinator or supramal controller would concern itself with the total rate of production and command high level

changes in operation to control the interaction between the subparts. For the NAS example, the National Air Traffic Control System Command Center (ATCSCC) acts as the supremal controller.

Figure 3 illustrates a high level interpretation of a hierarchical system decomposed on the basis of structure. Note that the local controllers could be behavior-based or schema-based controllers (as discussed in Section 2.7), neural network controllers (as discussed in Section 2.8), fuzzy logic controllers (as discussed in Section 2.9), or expert system controllers (as discussed in Section 2.10). Additionally, if the supremal controller is a discrete event system, and the local controllers are continuous systems, then a hybrid system results (as discussed in Section 2.3).

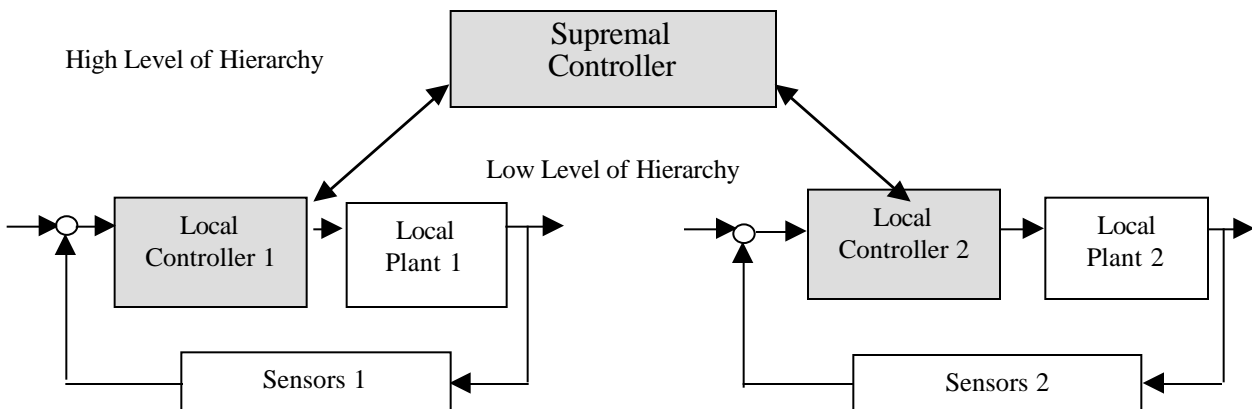


Figure 3. Coordination of two controllers by a hierarchical supremal controller.

Decomposition on the basis of levels of control partitions tasks either rate of disturbances into a system, or by the level, type or sophistication of a task. A good example of such a decomposition is that of an aircraft's flight control system. The flight control system of an aircraft must first close inner loops which stabilize the aircraft. These loops generally deal with the fastest disturbances. Furthermore, these inner loops are purely feedback control algorithms and require little cognitive ability. Once the aircraft is stabilized, the next control laws must enable the aircraft to maintain constant speed, altitude, and heading. Finally, the outermost loops deal with the guidance of the aircraft to make it fly to fixes or along routes. In this case, each level of control receives commands from the next highest level and then generates commands for the next lowest level. The lowest level control algorithm then manipulates the actuators of the system. Figure 4 illustrates the hierarchical decomposition based on control partitions of tasks in an aircraft; such a design is typical in behavior-based and schema-based control systems (as discussed in Section 2.7).

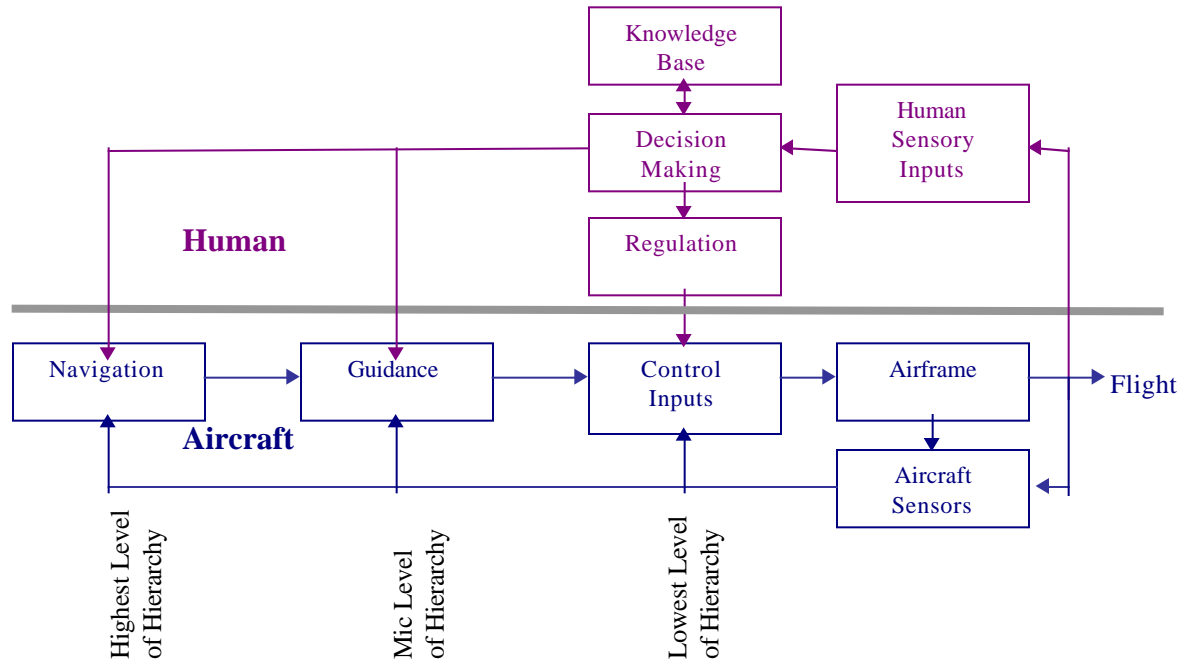


Figure 4. Hierarchical process for human decision making while flying an aircraft.

Decomposition on the basis of levels of influence is essentially a partitioning of the control into multiple levels of priority or importance. These levels of influence, referred to as ‘strata’ have two characteristic features. First, individual strata have quite different objectives and tasks; and second, the division into strata results in a priority structure with the higher strata having a priority over the lower strata. An example of levels of influence decomposition may be found in software engineering where the tasks of a code may be assigned to threads with differing levels of priority depending on the system needs.

2.1.2 Literature in Hierarchical Control Theory

Examples of hierarchical control have been presented in numerous publications [BPC94, GLS95, HH92, IM88, L97, M87, M93, SH89, SK88, SK90, TS77, Ty93]. Hierarchical control techniques can be applied to the control of an aircraft [S93], as well as ATC [SCH88, SMT95, KrS99].

[BPC94] Blaasvaer, Pirjanian, and Christensen, “AMOR – An Autonomous Mobile Robot Navigation System”

Key Words: Hierarchical Control, Pilot/Navigator/Reactive Controller, Behaviors, Mobile Robot

[GLS95] Godbole, Lygeros, and Sastry, “Hierarchical Hybrid Control: A Case Study”

Key Words: Hierarchical Control, Hybrid Systems, Intelligent Vehicle Highway System

[HH92] How and Hall, “Local Control Design Methodologies for a Hierarchic Control Architecture”

Key Words: Hierarchical Control, Space Structures, Two-Level Architecture

[IM88] Isik and Meystel, “Pilot Level of a Hierarchical Controller for an Unmanned Mobile Robot”

Key Words: Hierarchical Control, Robotics, Navigation

[KuS99] Kuwata and Sugimoto, “Intelligent Techniques in Air Traffic Management”

Key Words: Hierarchical Control, Air Traffic Control, Air Traffic Management, Agents

[L79] Larson, “A Survey of Distributed Control Techniques”

Key Words: Distributed Control, Survey, Hierarchical Control, Game Theory, Periodic Coordination

[M87] Meystel, “Theoretical Foundations of Planning and Navigation for Autonomous Robots”

Key Words: Hierarchical Control, Robotics, Path Planning, Nesting

[M93] Meystel, “Nested Hierarchical Control”

Key Words: Hierarchical Control, Robotics, Path Planning

[SMT95] Sastry, Meyer, Tomlin, *et al*, “Hybrid Control in Air Traffic Management Systems”

Key Words: Hybrid Control, ATM, Hierarchical System, Conflict Detection and Resolution

[SH89] Skillman and Hopping, “Dynamic Composition and Execution of Behaviors in a Hierarchical Control System”

Key Words: Hierarchical Control

[SK88] Skillman, Kohn, and Graham, “Hierarchical Control of a Mobile Robot with a Blackboard Based System”

Key Words: Hierarchical Control, Blackboard Architecture

[SK90] Skillman, Kohn, Nguyen, *et al*, “Class of Hierarchical Controllers and Their Blackboard Implementations”

Key Words: Hierarchical Control, Blackboard, Recursive Hierarchy, Goal-Driven Controllers

[SCH88] Steeb, Cammarata, Hayes-Roth, *et al*, “Distributed Intelligence for Air Fleet Control”

Key Words: Distributed Control, ATC, hierarchical control, situation complexity

[S93] Stengel, “Towards Intelligent Flight Control”

Key Words: Hierarchical Control, Aircraft Application, expert systems

[TS77] Teneketzis and Sandell, “Linear Regulator Design for Stochastic Systems by a Multiple Time-Scales Method”

Key Words: Hierarchical Control

[Ty93] Tyrrell, “The Use of Hierarchies for Action Selection”

Key Words: Hierarchical Control, Robotics, Action Selection, Switching, Animal Behavior, Compromise

2.2 Distributed Control Systems

2.2.1 Theory of Distributed Control Systems

Distributed control, or distributed problem solving, involves the use of decentralized, loosely coupled controllers or problem solvers. The system is decentralized, so both the control and the data are functionally and often geographically distributed. Independent controllers have their own local memory, and no one controller has enough memory to store the entire data of the system. Opposite from a centralized controller, no one element of the decentralized control system is capable of solving the entire problem – as well, no one element becomes a bottleneck for a solution. Information must be shared to allow the group as a whole to solve the control problem; thus, a communication protocol is defined for distributed control. The controllers are loosely coupled in that the controllers spend more of the time computing (e.g., solving a conflict problem) rather than communicating; this generally assumes that communication is slower than computation, which has historically been the case.

In distributed control systems, communication is usually asynchronous communication and locally transmitted, since bandwidth limitations make it impossible for all of the controllers to communicate with each other continuously all the time. Communication broadcasts consist of information that is distributed indiscriminately, so that all receivers within a given range receive the same information.

The communications may proceed through a contract based communication mechanism [DS83], or may follow a more advanced negotiation strategy like principled negotiation (see Section 2.6).

Figure 5 illustrates a distributed control system for ATC. Communications occur only between aircraft that are connected with a communications link (e.g., those aircraft that can transmit and receive ADS-B messages); in the figure, this is marked with a two headed arrow. It is possible that some aircraft are not equipped to transmit ADS-B messages but are equipped to receive messages, so the communications link indicates an incoming arrow only. Rules can be derived so that aircraft proceed to resolve conflicts based on equipage, headings, speeds, and relative positions. Conflicts local to one cluster of aircraft are not known by other aircraft outside the cluster.

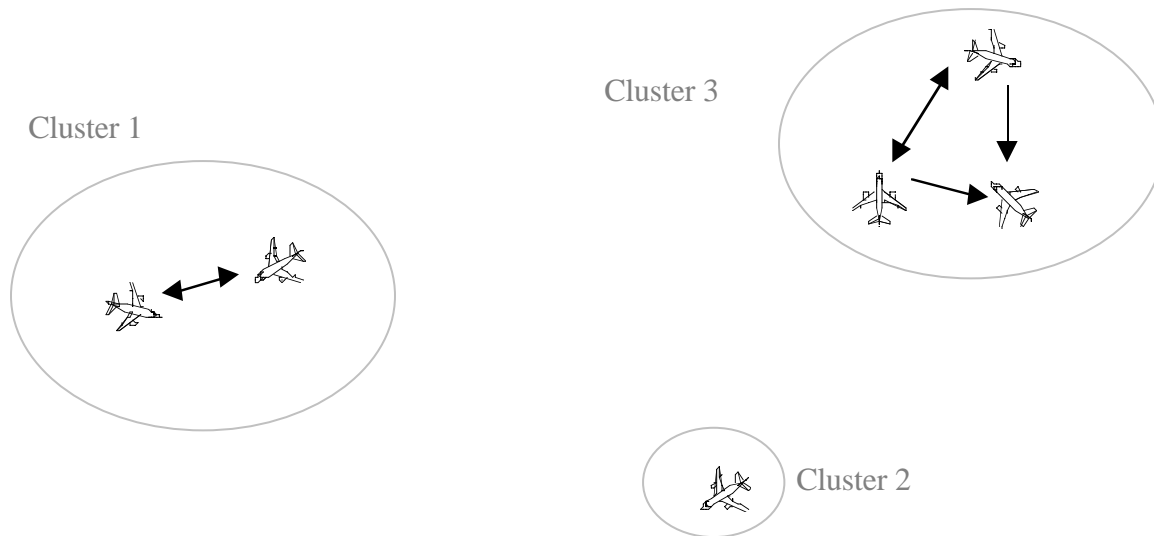


Figure 5. Distributed control system ATC application.

As pointed out in the literature [R94], a decentralized control system may exhibit properties that imply a centralized controller is in place. When people observe patterns or structure in the world around them, they sometimes attribute the patterns or structure to a leader who is organizing or orchestrating the system. For instance, when people see patterns in society, they associate the patterns with government orchestrating the pattern through rules, laws, policies, or infrastructure. In decentralized control, “emergent objects” may form based on the local interactions of individual control laws. For instance, traffic jams may emerge and may change location as cars pass into and out of the traffic jam. A traffic jam is not defined by a constant set of cars interacting, in fact, cars pass into and out of a traffic jam while the traffic jam remains an emergent object even after an individual car has past. Furthermore, there are no centralized control laws or rules that specifically designed to cause traffic jams.

Interactions of lower level objects (not the actual objects themselves) define an emergent object. Emergent objects and patterns may be mistaken for policies or properties set by a centralized controller, which is not the case for many decentralized systems. To affect emergent objects, a centralized control law may be imposed at a hierarchical level (above a centralized subsystem) to affect emergent objects and their properties by either creating changes to the environment of the system under centralized control or by creating changes in the way individual objects are allowed to interact. This in turn can cause new or different emergent objects or patterns, or no emergent objects or patterns. An example is how timed lights control the traffic entering freeways to deter clusters of traffic that might trigger a traffic jam. Thus, the designer of a decentralized control system often employs a paradigm called “analysis by synthesis” [HS87], where by building (synthesis) a simulation of a phenomenon a well-reasoned explanation for the behavior of a system (analysis) can be performed.

2.2.2 Literature in Distributed Control Theory

A survey of distributed control techniques appears in [L79] and for robotics applications in [CAO97, S98]. Distributed control has been used in many applications [E86, DHJ81, L86, L98, LC81, P98, R94, SD81, SM97, Tu93, Tu98, UFA92]. In particular, distributed control has been applied to the ATC domain by several researchers [AKO96, AKMO97, BLM00, CMS83, DDMS95, DS83, FL86, HvGR96, HvGR99, KPB00, SCH88]. The scalability of distributed control systems is discussed in [N94].

[AKO96] Adams, Kolitz, and Odoni, “Evolutionary Concepts for Decentralized Air Traffic Flow Management”

Key Words: Decentralized Control, Distributed Control, Evaluation Metrics

[AKMO97] Adams, Kolitz, Milner, and Odoni, “Evolutionary Concepts for Decentralized Air Traffic Flow Management”

Key Words: Collaborative Decision Making, Decentralized Control, ATM, Free Flight, Flow Management

[BLM00] Bilimoria, Lee, et al, “Comparison of Centralized and Decentralized Conflict Resolution Strategies for Multiple-Aircraft Problems”

Key Words: Free Flight, CD&R, Centralized Control, Decentralized Control

[CMS83] Cammarata, McArthur, and Steeb, “Strategies of Cooperation in Distributed Problem-Solving”

Key Words: Distributed Control, ATC, Cooperation

[CAO97] Cao, Fukundaga, and Kahng, “Cooperative Mobile Robots: Antecedents and Directions”

Key Words: Robotics, Cooperative Control Techniques, Survey, Distributed Control, Decentralized Control

[DHJ81] Davies, Holler, Jensen, *et al*, *Distributed Systems – Architecture and Implementation*

Key Words: Distributed Systems, Hierarchy, Distributed Control, Protocols, Applications

[DS83] Davis and Smith, “Negotiation as a Metaphor for Distributed Problem Solving”

Key Words: Distributed Problem Solving, Negotiation, ATC, Protocols, Contract Net Protocol

[DDMS95] Debelack, Dehn, Muchinsky, and Smith, “Next Generation Air Traffic Control Automation”

Key Words: Distributed Control, hardware, software, computer system requirements, CD&R

[E86] Elfes, “A Distributed Control Architecture for an Autonomous Mobile Robot”

Key Words: Distributed Control, Hierarchical Control, Blackboard Architecture, Robotics

[FL86] Findler, N.V. and Lo, R., “An Examination of Distributed Planning in the World of Air Traffic Control”

Key Words: Distributed Problem Solving, Simulation Based Planning, ATC, Domino Effect

[HvGR96] Hoekstra, van Gent, and Ruigrok, “Conceptual Design of Free Flight with Airborne Separation Assurance”

Key Words: Free Flight, CD&R, Man-in-the-Loop Simulator Experiment

[HvGR99] Hoekstra, van Gent, and Ruigrok, “Designing for Safety: the ‘Free Flight’ Air Traffic Management Concept”

Key Words: Free Flight, CD&R, Man-in-the-Loop Simulator Experiment

[KPB00] Krozel, Peters, and Bilimoria, “A Decentralized Control Strategy for Distributed Air/Ground Traffic Separation”

Key Words: Free Flight, CD&R, Strategic, Alert Zones, Separation Assurance, Distributed Control, DAG-TM

- [L79] Larson, "A Survey of Distributed Control Techniques" in *Distributed Control*
Key Words: Distributed Control, Survey, Hierarchical Control, Game Theory, Periodic Coordination
- [L98] Lesser, "Reflections on the Nature of Multi-Agent Coordination and Its Implications for an Agent Architecture"
Key Words: Distributed Systems, Architecture Design, Multi-Agent Coordination, Negotiation
- [LC81] Lesser, V. R. and Corkill, "Functionally Accurate, Cooperative Distributed Systems"
Key Words: Distributed Systems, Cooperative Control, Knowledge-Based Systems
- [L86] Lukas, *Distributed Control Systems*
Key Words: Distributed Control, Evolution, Process Control
- [N94] Neuman, "Scale in Distributed Systems" in *Readings in Distributed Computing Systems*
Key Words: Distributed Systems, Scalability, Coherence, Reorganization, Resources, Communication
- [P98] Parker, "ALLIANCE: An Architecture for Fault Tolerant Multi-Robot Cooperation"
Key Words: Behavior-Based Control, Distributed Systems, Multi-Robot Coordination, Cooperation, Fault Tolerance
- [R94] Resnick, *Turtles, Termites, and Traffic Jams*
Key Words: Decentralized Control, Traffic Jams, Coordination, emergent objects
- [SD81] Smith and Davis, "Frameworks for Cooperation in Distributed Problem Solving"
Key Words: Distributed Problem Solving, Cooperation, Task Sharing, Communication
- [SCH88] Steeb, Cammarata, Hayes-Roth, *et al*, "Distributed Intelligence for Air Fleet Control"
Key Words: Distributed Control, ATC, hierarchical control, situation complexity
- [SM97] Stothert and MacLeod, "Distributed Intelligent Control System for a Continuous-State Plant"
Key Words: Distributed Control, Distributed AI, protocols, a priori and operational knowledge
- [S98] Sycara, "Multiagent Systems"
Key Words: Distributed Systems, Multiagent systems, Control, Coordination, Communication
- [TS81] Tenney. and Sandell, "Strategies for Distributed Decisionmaking"
Key Words: Distributed Decisionmaking, Hierarchical Control, Teams, Abstraction, Coordination
- [Tu93] Turner, "Context-Sensitive Reasoning for Autonomous Agents and Cooperative Distributed Problem Solving"
Key Words: Distributed Problem Solving, Autonomous Agents, Cooperation
- [Tu98] Turner, "Context- Mediated Behavior for Intelligent Agents"
Key Words: Distributed Problem Solving, Autonomous Agents, Cooperation
- [UFA92] Ueyama, Fukuda, and Ahai, "Configuration of Communication Structure for Distributed Intelligent Robotic System"
Key Words: Distributed Control, Robotic Systems, Multiple Vehicles, Communications

2.3 Hybrid Control Systems

2.3.1 Theory of Hybrid Control Systems

Hybrid control address dynamical systems that include both discrete events as well as continuous differential equations. Figure 6 illustrates the general architecture of a hybrid control system. Hybrid control systems often take the form of a supervisor (a discrete event system) controlling a plant (a continuous state dynamical system). An interface between the two performs the functionality of Digital/Analog (D/A) and Analog/Digital (A/D) conversions between the discrete and continuous systems. In terms of ATC, aircraft are modeled as differential equations governed by continuous control laws. The flight mode changes between control laws, for instance, those changes that occur due to ATC or pilot-to-pilot communications, are modeled by discrete events. The actions of the controller are discrete events.

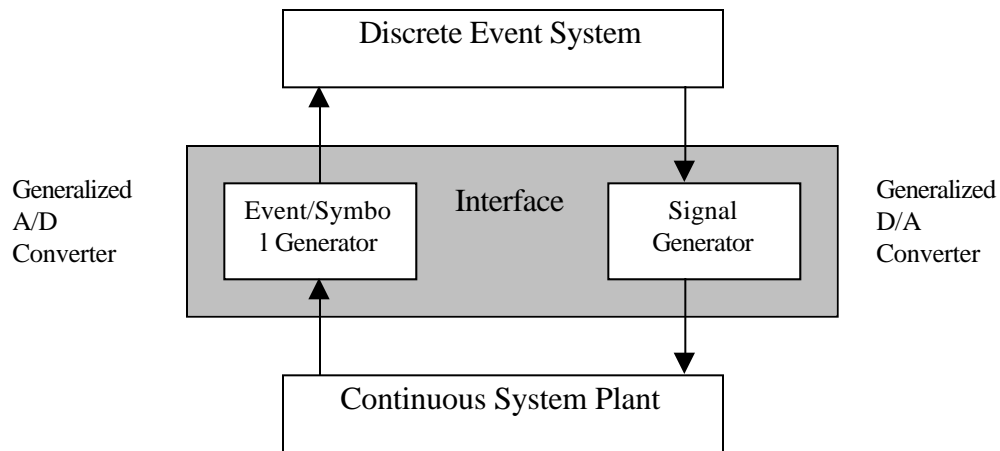


Figure 6. A hybrid control system.

2.3.2 Literature in Hybrid Control Systems

Many of the publications related to hybrid systems have been covered in Springer-Verlag Lecture Notes in Computer Science [GNRR93, AKNS95, AHS96, AKNS97, AKL99]. Hybrid control has been applied in a decentralized control system for ATC/ATM by several authors [KRM97, TPS98, PTS96, SMC95]. Theory for the stability of hybrid control systems, which typically involves the use of multiple Lyapunov functions, has been investigated by several researchers [Bra97, EM99, HLM97, JR98, KV96, YMH98]. The theory of hybrid control systems is considered to be in a nascent state, with most publications published in the last five years.

[AHS96] Alur, Henzinger, and Sontag, Eds., *Hybrid Systems III*
Key Words: Hybrid Systems, Lecture Notes

[AKNS95] Antsaklis, Kohn, Nerode, and Sastry, Eds., *Hybrid Systems II*
Key Words: Hybrid Systems, Lecture Notes

[AKNS97] Antsaklis, Kohn, Nerode, and Sastry, Eds., *Hybrid Systems IV*
Key Words: Hybrid Systems, Lecture Notes

[AKL99] Antsaklis, Kohn, Lemmon, Nerode, and Sastry, Eds., *Hybrid Systems V*
Key Words: Hybrid Systems, Lecture Notes

[Bra97] Branicky, “Stability of Hybrid Systems: State of the Art”

Key Words: Hybrid Control Systems, Stability, Lyapunov Functions, Theorems

[BBM98] Branicky, Borkar, and Mitter, “A Unified Framework for Hybrid Control: Model and Optimal Control Theory”

Key Words: Hybrid Control, Optimal Control

[EM99] Eker and Malmberg, “Design and Implementation of a Hybrid Control Strategy”

Key Words: Hybrid Control Systems, Lyapunov Stability, PID Controllers, Switching Controllers

[GNRR93] Grossman, Nerode, Ravn, and Rischel, Eds., *Hybrid Systems*

Key Words: Hybrid Systems, Lecture Notes

[HLM97] Hyemann, Lin, and Meyer, “Viability of Controllers for Hybrid Machines”

Key Words: Hybrid Control Systems, Zenoness, Theorems

[JR98] Johansson and Rantzer, “Computation of Piecewise Quadratic Lyapunov Functions for Hybrid Systems”

Key Words: Hybrid Control Systems, Stability

[KRM97] Kohn, Remmel, Moser, and Cummings, “Free Flight ATC using Hybrid Agent Systems”

Key Words: Hybrid Systems, ATC, Free Flight, Agents, Lagrangian, Distributed Control

[KV96] Kourjanski, and Varaiya, “Stability of Hybrid Systems”

Key Words: Hybrid Systems, Stability

[TPS98] Tomlin, Pappas, and Sastry, “Conflict Resolution for Air Traffic Management: A Study in Multiagent Hybrid Systems”

Key Words: Hybrid Control, Decentralized Control, ATM, Game Theory

[PTS96] Pappas, Tomlin, and Sastry, “Conflict Resolution for Multi-Agent Hybrid Systems”

Key Words: Hybrid Control, Unsafe Set, CD&R, Cooperative Conflict Resolution, Game Theory

[SMT95] Sastry, Meyer, Tomlin, *et al*, “Hybrid Control in Air Traffic Management Systems”

Key Words: Hybrid Control, ATM, Hierarchical System, Conflict Detection and Resolution

[YMH98] Ye, Michel, and Hou, “Stability Theory for Hybrid Dynamical Systems”

Key Words: Hybrid Control Systems, Lyapunov Stability, Lagrange Stability

2.4 Control by Permission, Periodic, and Supervisory Control Systems

2.4.1 Theory of Control by Permission, Periodic, and Supervisory Control

Control by permission, periodic control, and supervisory control are similar in that they have a hierarchical structure of a high level controller or coordinator overseeing one or more lower level systems. They differ slightly in how and when high level and low level systems interact.

Control by permission is a process where a higher level controller or coordinator is under control of a system and assigns tasks to one or more subsystems. The overall objective function of the high level control is optimized by making tradeoffs between assignments to subsystems. Although it might be suboptimal, control by permission allows the subsystem to request a control strategy different than the assigned strategy by proposing a new strategy and requesting permission from the high level controller. If the request is reasonable with respect to the constraints and objectives of the high level controller, permission is granted; otherwise the subsystem must abide by the original directives of the

higher level controller. Control by permission is used today in ATC when pilots request an alternate route from the filed flight plan. ATC can grant permission to use the alternate route or ATC may deny the request.

Periodic control or periodic coordination is a hierarchical process where on some periodic interval a coordination controller (usually an automatic system and not a human) will check the conditions of one or more lower level control systems and update their goals and parameters to meet the overall system objectives. The update rates of the lower level control systems is much faster than the periodic control interval. Lower level systems can interact and affect each other's state variables and/or the achievement of each other's goals. Figure 7 illustrates the structure of a periodic control system. Periodic control is similar to supervisory control; however, supervisory control is in general asynchronous and does not operate on a periodic interval.

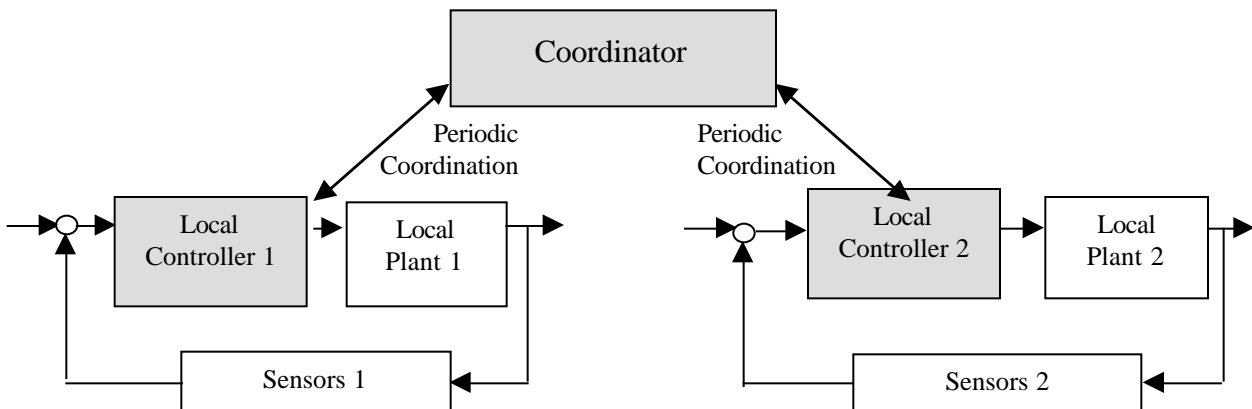


Figure 7. A periodic control system overseeing multiple closed loop subsystems.

Supervisory control is a combined human and computer control system where the human controls one or more vehicles typically from a geographically remote location. Generally, inner closed loop control systems allow the supervisor to work as a monitor. Monitoring features can provide information to the human for state feedback, fault detection, and in some cases visual feedback. A supervisory control system typically provides the human with flexible methods to define the desired trajectory or performance of the vehicle or vehicles being controlled. Supervisory control systems are typical in teleoperation of robots for dangerous environments, deep sea exploration using robotic underwater vehicles, and the control of one or several remotely piloted air vehicles.

2.4.2 Literature in Control by Permission, Periodic, and Supervisory Control

Control by permission is discussed in [SMO97]. Periodic control is discussed in [L79]. Supervisory control systems have been applied in several applications as in [JM95, MA97, NA99, RJM88, Ta99, YNS86].

[JM95] Jones and Mitchell, "Human-Computer Cooperative Problem Solving: Theory, Design, and Evaluation of an Intelligent Associate System"

Key Words: Supervisory Control, Human-in-Charge, Intelligent Associate

[L79] Larson, "A Survey of Distributed Control Techniques"

Key Words: Periodic Coordination, Distributed Control, Survey, Hierarchical Control, Game Theory

[MA97] Moody and Antsaklis, “Supervisory Control Using Computationally Efficient Linear Techniques: A Tutorial Introduction”

Key Words: Supervisory Control, Discrete Event Systems, Petri Nets

[NA99] Neves and Aguilar-Martin, “Qualitative Event-Based Expert Supervision for Transient Condition Monitoring”

Key Words: Supervisory Control, Expert Supervision

[RJM88] Rubin, Jones, and Mitchell, “OFMspert: Inference of Operator Intentions in Supervisory Control using a Blackboard Architecture”

Key Words: Supervisory Control, Operator Function Models, Intent Inference

[SMO97] Smith, McCoy, Orasanu, *et al*, “Control by Permission: A Case Study of Cooperative Problem Solving in the Interactions of Airline Dispatchers with ATCSCC”

Key Words: Control by Permission, ATC, Cooperative Problem Solving, Shared Understanding

[Ta99] Takai, “Minimizing the Set of Local Supervisors in Fully Decentralized Supervision”

Key Words: Decentralized Control, Supervisory Control, Discrete Event System

[YNS86] Yoerlger, Newman, and Slotine, “Supervisory Control System for the JASON ROV”

Key Words: Supervisory Control, Underwater Vehicle, JASON, 3D Guidance, Sliding Mode Control

2.5 Collaborative Decision Making Control Systems

2.5.1 Theory of Collaborative Decision Making Control Systems

Collaborative Decision Making (CDM) systems involve two or more systems working together to solve a problem. In most collaborative systems, partial knowledge is the rule and not the exception [Gr96]. That is, no one system holds all the knowledge about the problem, and thus cannot solve the problem without working in collaboration with the other system(s). There are a few implicit assumptions for collaborative systems that allow them to work: (1) systems that compose the collaborative system must make a commitment to solving the problem, and (2) communication, either explicit or implicit, is needed in order to express commitments and responsibilities when these items can vary or are negotiated.

Collaborative Decision Making (CDM) is a process of two or more parties (agents, workers, controllers, etc.) working together in a problem solving task. For the ATC/ATM domain, CDM typically refers to one party from the FAA and another from the airlines (dispatcher, operations coordinator). However, Figure 8 illustrates all three types of collaboration that are common for the ATC/ATM domain.



Figure 8. Three types of collaboration between the AOC, Flight Deck (FD), and ATM.

The types of ATC/ATM problems that may be worked in collaboration include:

- Collaborative Routing (around weather, congestion, etc.),
- Collaborative Departure Scheduling,
- Collaborative SUA Scheduling [RS99],
- Collaborative Arrival Planning [CEN98, QZ98, ZBE98], and
- Post-Operations or Real-Time-Operations Feedback.

The collaborative decision making system also insures that each of the collaborators is using a consistent set of data. For example, NAS status, weather, equipment, and delay data. Collaborative decision making systems do not introduce any new control theory into the problem of controlling traffic in the NAS; rather, they offer the ability to coordinate actions and share information which each party uniquely has access to. CDM also includes developing solutions that satisfy each party's unique objectives. CDM essentially keeps the human in the loop while allowing the humans to access the automation aids that they normally use at their workstations.

2.5.2 Literature in Collaborative Decision Making Control Systems

Communications systems that can facilitate CDM are discussed in [CEN98, GGW97, KrS99, KSD99, Wa97, ZBE98]. The information requirements, costs, and benefits of CDM are discussed in [AKMO97, BCW99, FANG97, FHK98, FKL98, Gr96, SML97]. No papers discuss stability issues related to CDM.

[AKMO97] Adams, Kolitz, Milner, and Odoni, "Evolutionary Concepts for Decentralized Air Traffic Flow Management"

Key Words: Collaborative Decision Making, Decentralized Control, ATM, Free Flight, Flow Management

[BCW99] Beatty, Corwin, and Wambsganss, "Collaborative Decision-Making: A Success Story of an Airline-FAA Partnership"

Key Words: Collaborative Decision Making, Ground Delay Program, AOCnet, ETMS, OAG, Cost/Benefits

[CEN98] Carr, Erzberger, and Neuman, "Delay Exchanges in Arrival Sequencing and Scheduling"

Key Words: Collaborative Arrival Planning, Data Exchange, CTAS

[DGP99] Duley, Galster, Parasuraman, and Smoker, "En Route ATC Information Requirements for Participation in Future Collaborative Decision Making"

Key Words: Collaborative Decision Making, Information Requirements, Human Factors, Human-Centered

[FKL98] Falcone, Kollman, Leber, *et al*, "Demonstrating an Improved Weather Awareness System for CDM"

Key Words: Collaborative Decision Making, Collaborative Re-Routing, Weather Awareness, Cost/Benefits

[FHK98] Fan, Hyams, and Kuchar, "Study of In-Flight Replanning Decision Aids"

Key Words: Collaborative Decision Making, Time Critical Events, Weather, Replanning

[FANG97] FMS-ATM Next Generation (FANG) Team, *Airline Operational Control Overview*

Key Words: AOC, Operational Overview, National Routing Program, Data Exchange, Dynamic Route Planning

[GGW97] Green, Goka, and Williams, "Enabling User Preferences through Data Exchange"

Key Words: Data Exchange, CTAS, Free Flight

[Gr96] Grosz, "Collaborative Systems"

Key Words: Collaborative Systems, Distributed AI, Intentions, Partial Knowledge, Responsibilities, Commitment

[KrS99] Krozel and Schleicher, “An Airspace Visualization Tool for Collaborative Decision Making”
Key Words: Collaborative Decision Making, Visualization, Weather, Asynchronous Communication

[KSD99] Krozel, Schleicher, and Dow, “Collaborative Decision Making Airspace Visualization Tool”
Key Words: Collaborative Decision Making, Visualization, Weather, Asynchronous Communication

[QZ98] Quinn and Zelenka, “ATC/Air Carrier Collaborative Arrival Planning”
Key Words: Collaborative Arrival Planning, CTAS, ATC

[R99] Reilly, “Collaboration: Developing a Global Information Exchange”
Key Words: Collaboration, Teleconferencing, e-mail, e-collaboration, groupware

[RS99] Rock and Sullivan, “Negotiation Automation for Special Use Airspace”
Key Words: Collaborative Decision Making, SUA, Scheduling, DoD, FAA, Communication and Coordination

[SML97] Smith, McCoy, and Layton, “Brittleness in the Design of Cooperative Problem-Solving Systems: The Effects of User Performance”
Key Words: Cooperative Problem Solving, Brittleness, Subject Expert Comments, Task Analysis

[Wa97] Wambsganss, M., “Collaborative Decision Making Through Dynamic Information Transfer”
Key Words: Collaborative Decision Making, Traffic Flow Management, War Gaming, Distributed Planning

[ZBE98] Zelenk, Beatty, and Engelland, “Preliminary Results of the Impact of CTAS Information on Airline Operational Control”
Key Words: Collaborative Arrival Planning, Collaborative Decision Making, Data Exchange, CTAS, AOC

2.6 Game Theory and Principled Negotiation Systems

2.6.1 Game Theory and Theory of Principled Negotiation

Game theory and team theory may be applied to large-scale decentralized control systems broken down into lower order interacting subsystems. Team theory applies when there is one overall system cost composed of all the individual subsystem costs and individual costs are optimized in order to achieve the optimal team cost. An individual subsystem cost may be sub-optimal so that the entire system can achieve an optimal cost. Team theory may be used to model today’s positive ATC system, where ATM orchestrates the team of many individual aircraft. In contrast, game theory focuses on subsystems optimizing individual costs at the hope of the entire system cost is acceptable, even if suboptimal. A modern application of game theory uses principled negotiation for Free Flight, which is discussed next.

Principled negotiation involves the search by two or more agents (computers, pilots, air traffic controllers, etc.) for solutions that provide the greatest mutual gain with respect to each individual’s goals. Principled negotiation involves an iterative optimization process. As shown in Figure 9, agents start by considering the feasible set of actions that would benefit themselves, and assign a utility function to retain the benefits of actions. Agents repeatedly search for options that maximize mutual gain. During the process, when an agent finds an option that better meets its interests, then the option is posed to the other agents. As shown in Figure 10, the solution might be such that the optimal action for either agent may not suffice, but the overlap of feasible actions can still achieve mutual gain for both agents. The other agents evaluate the proposed option, accept it and implement the solution or reject it and pose an alternative option. When options are rejected the reasons for the rejection assist other agents in formulating a solution with mutual gain.

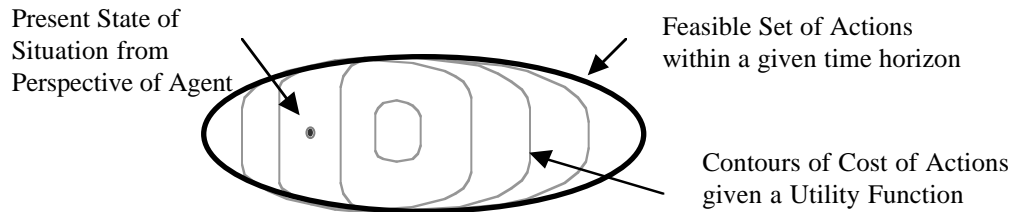


Figure 9. The options of an agent are represented in a state space with a utility function that determines the benefit of one state over another.

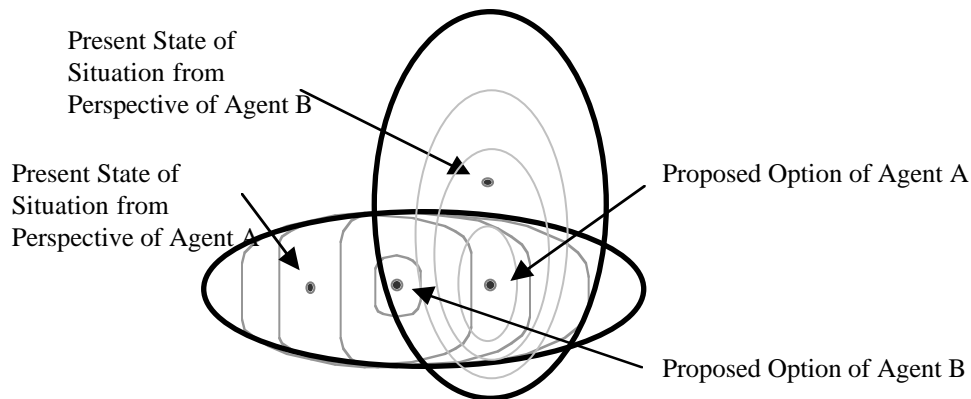


Figure 10. The proposed option of one agent is suggested to the other agent and a negotiation begins; iteratively, the negotiation settles into an agreed upon action.

2.6.2 Literature in Principle Negotiation

Early work on principled negotiation stems from the investigation in distributed artificial intelligence where researchers studied how multiple agents can interact intelligently [DS83, RG85, ZR91]. Game theory and team theory is discussed in the survey of Larson [L79].

Principled negotiation has been applied to the coordination of multiple aircraft in work at Princeton [SW93, WS94, WS96a, WS96b, WS99] and by others [DS83, HMG99]. Further applications are described in [LS96].

Most recently, automatic negotiation protocols which allow computers to negotiate directly with other computers have been researched [RZ94a, RZ94b, ZR96]. These protocols allow for individual programmers, corporations, government, or other entities to specify their user preference strategies for negotiation within a computer programs and to then allow the negotiation process (most likely defined by the government, taking fairness, safety, and efficiency into account) to proceed through an automated mechanism (e.g., ADS-B message passing between computers).

[DS83] Davis and Smith, "Negotiation as a Metaphor for Distributed Problem Solving"

Key Words: Distributed Problem Solving, Negotiation, ATC, Protocols, Contract Net Protocol

[FHE98] Farley, Hansman, et al, "The Effect of Shared Information on Pilot/Controller Situation Awareness and Re-Route Negotiation"

Key Words: Free Flight, CDM, ATC, FD, Route Negotiation, Weather, CD&R, Empirical Study

[HMG99] Harper, Mulgund, Guarino, *et al*, "Air Traffic Controller Agent Model for Free Flight"

Key Words: Principled Negotiation, ATM, ATC, Collaborative Decision Making, CD&R

[JS98] Jacolin and Stengel, "Evaluation of a Cooperative Air Traffic Management Model using Principled Negotiation between Intelligent Agents"

Key Words: Principled Negotiation, ATM, agents, distributed systems

[L79] Larson, "A Survey of Distributed Control Techniques"

Key Words: Distributed Control, Survey, Hierarchical Control, Game Theory, Periodic Coordination

[SW93] Stengel and Wangermann, "Air Traffic Management as Principled Negotiation between Intelligent Agents"

Key Words: Principled Negotiation, ATC, agents, conflict detection and resolution

[WS94] Wangermann and Stengel, "Principled Negotiation between Intelligent Agents: A model for Air Traffic Management"

Key Words: Principled Negotiation, ATC, distributed systems, agents, expert system

[WS96a] Wangermann and Stengel, "Optimization and Coordination of Multi-Agent Systems Using Principled Negotiation"

Key Words: Principled Negotiation, ATC, distributed systems, agents, conflict detection and resolution

[WS96b] Wangermann and Stengel, "Distributed Optimization and Principled Negotiation for Advanced Air Traffic Management"

Key Words: Principled Negotiation, ATC, ATM, distributed systems, agents, conflict detection and resolution

[WS99] Wangermann and Stengel, "Optimization and Coordination of Multiagent Systems Using Principled Negotiation"

Key Words: Principled Negotiation, ATC, distributed systems, agents, conflict detection and resolution

[LS96] Lewis and Spich, "Principled Negotiation, Evolutionary Systems Design, and Group Support Systems: A Suggested Integration of Three Approaches to Improving Negotiations"

Key Words: Principled Negotiation

[CK91] Conry, Kuwabara, Lesser, and Meyer, "Multistage Negotiation for Distributed Constraint Satisfaction"

Key Words: Negotiation, Distributed Problem Solving

[RG85] Rosenschein and Genesereth, "Deals Among Rational Agents"

Key Words: Multi-Agent Interaction, Protocols, Distributed Artificial Intelligence

[RZ94a] Rosenschein, and Zlotkin, *Rules of Encounter*

Key Words: Automated Negotiation, Negotiation Protocols, Pareto Optimality, Stability, Theorems

[RZ94b] Rosenschein and Zlotkin, "Designing Conventions for Automated Negotiation"

Key Words: Automated Negotiation, Negotiation Protocols, Multi-agent Systems

[ZR91] Zlotkin and Rosenschein, "Cooperation and Conflict Resolution via Negotiation Among Autonomous Agents in Non-cooperative Domains"

Key Words: Automated Negotiation, Protocols, Distributed Artificial Intelligence

[ZR96] Zlotkin and Rosenschein, "Mechanisms for Automated Negotiation in State Oriented Domains"

Key Words: Automated Negotiation, Unified Negotiation Protocol, State Oriented Domains, Goals

2.7 Behavior-Based or Schema-Based Control Systems

2.7.1 Theory of Behavior-Based or Schema-Based Systems

Behavior-based and schema-based control involve tight coupling between sensor data and action for the control of immediate responses with higher level control actions taking over when immediacy is not needed. Figure 11 illustrates the general form of this controller. Generally, functional layers are formed as independent algorithms that operate asynchronously. Each layer performs a fundamental capability that allows the control system to exhibit higher and higher levels of competency.

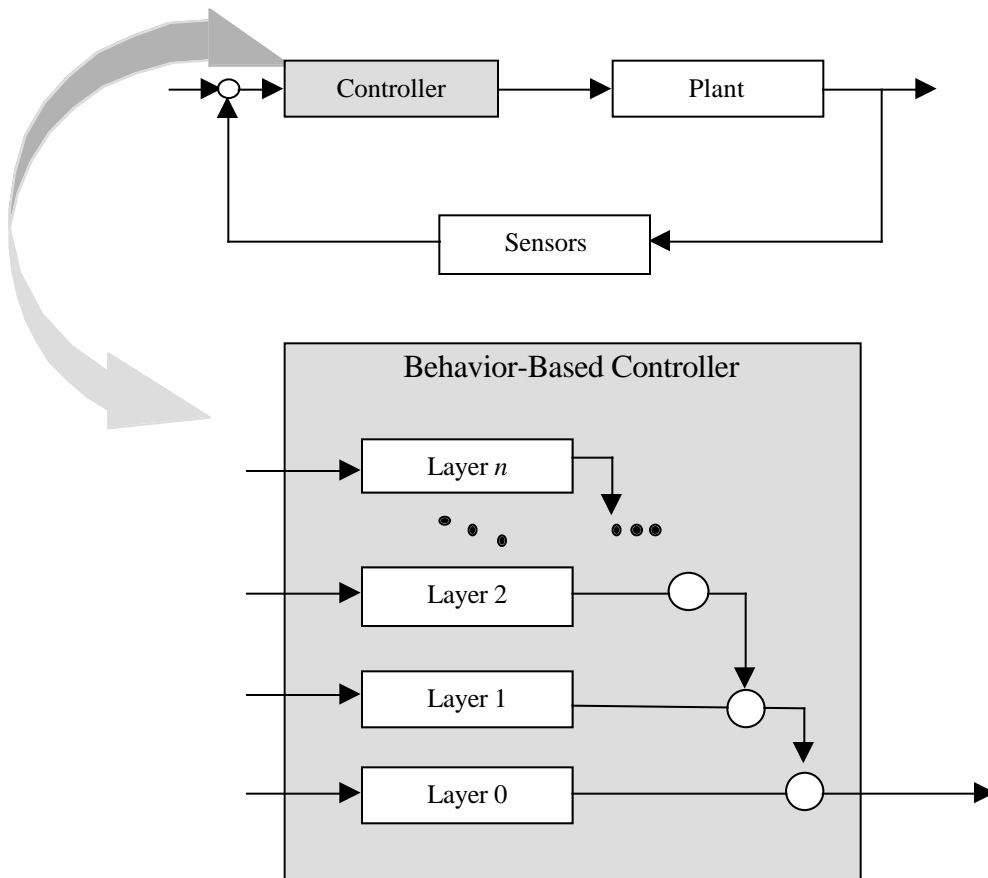


Figure 11. Behavior-Based or Schema-Based control establishes independent layers of functionality in a closed loop control system.

Behavior-based and schema-based techniques have primarily been used in robotics, where there are two primary functional breakdowns for control. Figure 12 illustrates the traditional horizontal decomposition, and Figure 13 illustrates the vertical decomposition. In the horizontal functional breakdown, a single or global model of the world (implicitly defined or defined through sensors) is built in order to form the basis for planning and task execution. In the vertical functional decomposition, each behavior has a model of the world as needed by the behavior. Behaviors are designed to perform specific tasks, and each behavior is designed not to know about any additional behaviors that might be active. In this way, both high level goals and low level goals can be actively pursued by two behaviors that are concurrently activated. Robustness exists when multiple behaviors exist that all achieve the same task with different approaches to control. The desired control actions from multiple layers of behaviors are coordinated through subsumption [Br86a], where higher level behaviors suppress or inhibit the outputs of lower level behaviors (when appropriate), or through command fusion [P90, PRK90].

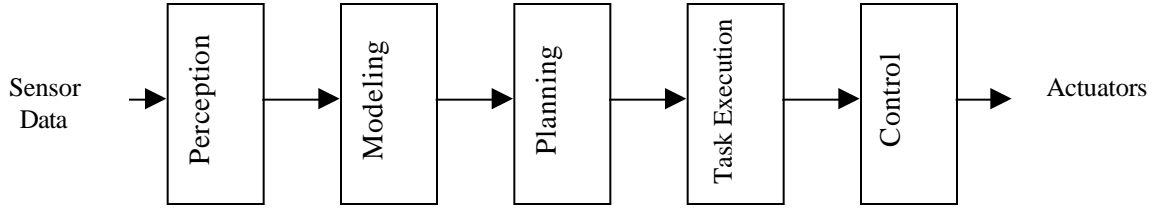


Figure 12. The horizontal decomposition of control of a vehicle.

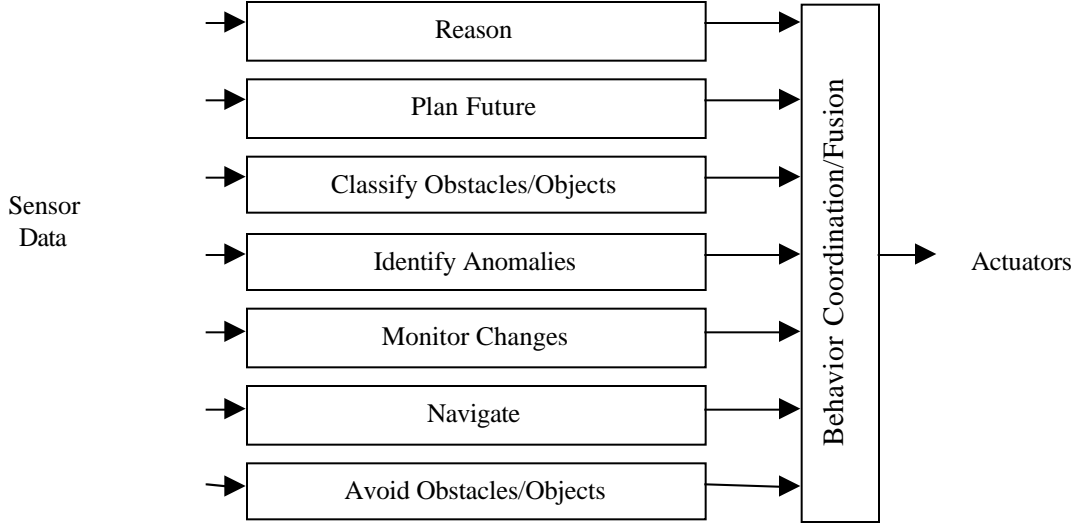


Figure 13. The vertical decomposition of control of a vehicle.

For the control of an aircraft or ATC, the lowest level behaviors would achieve conflict detection and resolution, while the higher level behaviors would perform guidance and control tasks. At this time, no such behavior-based aircraft control or ATC system has been demonstrated. However, there have been several researchers who have coordinated the actions of multi-robot systems using behavior-based control methods; these coordinated activities include formation control which inherently requires separation assurance between robots.

2.7.2 Literature in Behavior-Based or Schema-Based Systems

Most of the applications of schema-based and behavior-based control have been in robotics [A89, A89a, A89b, A89c, A89d, A90, Br86a, Br86b, Bee90, JF93, L87, P94, Ty89, Tu98, TBCJ93]. A few applications have been designed for 3D navigation of robots or aircraft [A89d, L87, Ty89, PKK92]. The coordination of multiple mobile robots, which is applicable to the ATC domain, is covered in [AB98, BA94, BA98, EUB97, M92, P92, P94, P98, TED94]. At this time, no formal theory for stability has been presented for behavior-based or schema-based control.

[An89] Anderson, *A Reflexive Behavioral Approach to the Control of a Mobile Robot*
Key Words: Behavior-Based Control, Mobile Robot, Collision Avoidance, Fusion

[A89a] Arbib, "Neuroscience in Motion: The Application of Schema Theory to Mobile Robots"
Key Words: Schema, Robotics, Obstacle Avoidance, Behaviors

[A89b] Arkin, "Motor Schema-Based Mobile Robot Navigation"

Key Words: Schema, Robotics, obstacle avoidance

[A89c] Arkin, "Navigation Path Planning for a Vision-Based Mobile Robot"

Key Words: Schema, Robotics, Obstacle Avoidance, Hierarchical Control System

[A89d] Arkin, "Three-Dimensional Motor Schema Based Navigation"

Key Words: Schema, Robotics, Obstacle Avoidance, 3D Motion, Reactive Control

[A90] Arkin, "The Impact of Cybernetics on the Design of a Mobile Robot System: A Case Study"

Key Words: Schema, Robotics, Obstacle Avoidance, Hierarchical Control System

[A98] Arkin, *Behavior-Based Robotics*

Key Words: Behavior-Based Control, Reactive Architectures, Robotics, Cooperation, Communication

[AB98] Arkin and Balch, "Cooperative Multiagent Robotic Systems"

Key Words: Schema-Based Control, Cooperation, Formation Keeping, Mobile Robots, UGV

[BA94] Balch and Arkin, "Communication in Reactive Multiagent Robotic Systems"

Key Words: Schema-Based Control, Cooperation, Communication, Mobile Robots

[BA98] Balch and Arkin, "Behavior-Based Formation Control for Multi-Robot Teams"

Key Words: Schema-Based Control, Cooperation, Formation Keeping, Mobile Robots, UGV

[Bee90] Beer, *Intelligence as Adaptive Behavior*

Key Words: Neural Network Control, Robotics, Navigation, Behaviors

[Br86a] Brooks, "A Robust Layered Control System For A Mobile Robot"

Key Words: Behaviors, Layered Control, Asynchronous

[Br86b] Brooks, *Achieving Artificial Intelligence Through Building Robots*

Key Words: Behavior-Based Control, Robotics

[JF93] Jones and Flynn, *Mobile Robots*

Key Words: Mobile Robots, Design, Engineering, Control, Applications

[EUB97] Evans, Unsal, and Bay, "A Reactive Coordination Scheme for a Many-Robot System"

Key Words: Behavior-Based Control, Multi-Robot Coordination, Broadcast Communications

[L87] Loch, *Design of a Reflexive Hierarchical Control System for an Autonomous Underwater Vehicle*

Key Words: Reflexive Control, 3D Navigation, Collision Avoidance

[Mae92] Maes, "Behavior-Based Artificial Intelligence"

Key Words: Behaviors, Robotics, Navigation

[Mat92] Mataric, "Minimizing Complexity in Controlling a Mobile Robot Population"

Key Words: Behavior-Based Control, Multiple Robots, Coordination

[P92] Parker, *Local versus Global Control Laws for Cooperative Agent Teams*

Key Words: Behavior Based Control, Multi-Vehicle Coordination, Cooperation

[P94] Parker, *Heterogeneous Multi-Robot Cooperation*

Key Words: Behavior Based Control, Multi-Vehicle Coordination, Cooperation

[P98] Parker, "ALLIANCE: An Architecture for Fault Tolerant Multi-Robot Cooperation"

Key Words: Behavior-Based Control, Distributed Systems, Multi-Robot Coordination, Cooperation, Fault Tolerance

[P90] Payton, “Internalized Plans: A Representation for Action Resources”

Key Words: Behavior-Based Control, Mobile Robots, Route Planning, Subsumption Architecture

[PB91] Payton and Bihari, “Intelligent Real-Time Control of Robotic Vehicles”

Key Words: Behavior-Based Control, Mobile Robots, Route Planning, Subsumption Architecture

[PKK92] Payton, Keirse, Kimble, Krozel, and Rosenblatt, “Do Whatever Works: A Robust Approach to Fault-Tolerant Autonomous Control”

Key Words: Behavior-based Control, Mobile Robots, Fault Tolerance, Subsumption Architecture, 3D Navigation

[PRK90] Payton, Rosenblatt, and Keirse, “Plan Guided Reaction”

Key Words: Behavior-Based Control, Mobile Robots

[Tu98] Turner, “Context- Mediated Behavior for Intelligent Agents”

Key Words: Distributed Problem Solving, Autonomous Agents, Cooperation, Behaviors

[TBCJ93] Turner, Blidberg, Chappell, and Jalbert, “Generic Behaviors: An Approach to Modularity in Intelligent Systems Control”

Key Words: Behavior-Based Control, Autonomous Underwater Vehicle, EAVE

[TED94] Turner, Eaton, and Dempsey, “Handling Unanticipated Events in Single and Multiple AUV Systems”

Key Words: Behavior-Based Control, Multiple Vehicles, AUVs, Conflict Detection and Resolution

[Ty89] Tynor, “Reflexive Navigation for Autonomous Aircraft”

Key Words: Schema, Robotics, 3D Motion

2.8 Neural Network Control Systems

2.8.1 Theory of Neural Network Control Systems

Neural networks are useful for control system design where plant dynamics are difficult to model. This is especially true in process industries. Often process control applications are difficult to model using first principles, and therefore, mathematical models which would provide insight into the dynamic characteristics of the plant are not available. The lack of a well defined mathematical model precludes the use of conventional control techniques which opens the door for neural networks. Neural networks provide a generic approach for building controllers when only historical data or test data for modeling are available. While classical approaches still can be applied if sophisticated techniques such as system identification are employed to develop a plant model, the neural networks appear to be easier to implement for practicing engineers. As shown in Figure 14, the neural network controller can be placed in the typical position for a closed loop control system.

There are several types of neural networks that can be applied to control systems:

- Multi-layer perceptron
- Kohonen’s self-organizing map
- Hopfield network
- Boltzman machine, and
- Cerebellar Model Articulation Controller (CMAC).

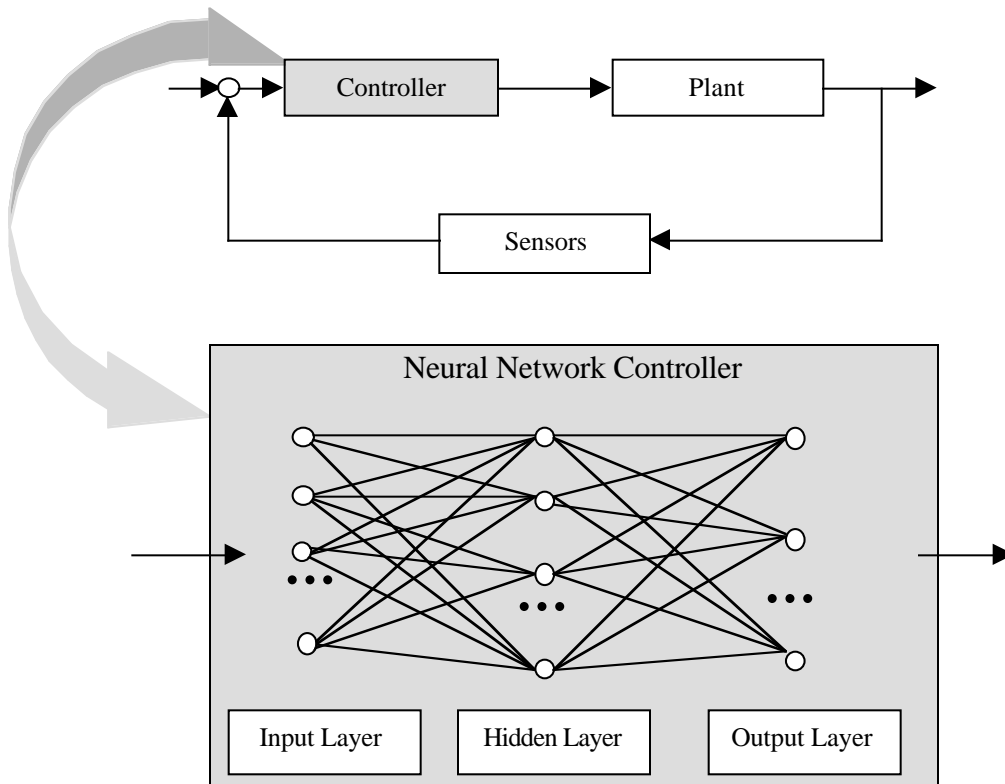


Figure 14. General framework for a neural network controller in a closed loop control system.

The multi-layer perceptron consists of a collection of neurons that are organized in layers with feedforward connections from one layer to another. The multilayer perceptron can be used to implement a trainable nonlinear function because large classes of continuous functions can be represented by a multilayer perceptron. The universal function approximation property of multilayer neural networks states that any smooth function can be approximated arbitrarily closely on a compact set using a two-layer neural network with the appropriate weights [LJY99]. This is an important property for the design of neural network closed loop controllers. However, there is a difficulty with such a perceptron in that there is no systematic method for determining the number of nodes, number of layers, or exact weights required to approximate a given function. Therefore trial and error data are required, or a learning algorithm is needed with training data. Learning is performed by giving the network an input and a corresponding desired output. Then, the weights within the various nodes are adjusted so that the perceptron yields the proper system output. Generally, specific problem related algorithms must be developed to train perceptrons.

Kohonen's self-organizing map is a type of neural network that consists of one layer neurons that are connected to the system input. There are also internal connections between the layer. These connections between neighboring neurons are obtained through a learning process. Generally, Kohonen's self-organizing map is used to classify data or signals. In particular, the self-organizing map classifies the dynamic response of a system or the time distribution of control system performance.

More sophisticated neural networks such as the Boltzman machine are also available. The primary distinction between the Boltzman machine and the less sophisticated perceptron is that the perceptron becomes a static entity once the training is finished – the weights within the neural net are fixed. The Boltzman machine is a dynamic system where arbitrary connections exist between the neurons. There may also be dynamics within the nodes. In this way, the inputs and desired responses are given and

the weights are adjusted until the machine responds as desired. Typical uses of the Boltzman machine include pattern-recognition and optimization.

The CMAC is analogous to the perceptron. The CMAC is modeled after the functional method that the cerebellum uses to control animal movement. It involves an associative memory whose inputs in control applications are set points and measured variables that are used to address a memory where the appropriate manipulated variables are stored. Each input is first mapped to a set of associated cells. The outputs from the cells are weighted and summed together to produce the CMAC's output. Training is accomplished in a manner similar to that of the perceptron. CMAC effectively uses a table lookup to generate the outputs and therefore any non-linear function can be approximated. Unfortunately, table lookups often require considerable computer memory. To avoid large memory sizes, hash tables are used to store the data. The table lookup is also a main advantage of the CMAC, because table lookup is inherently fast. This speed gives CMAC the potential to control real-time plants.

2.8.2 Literature in Neural Network Control Systems

A general introduction to neural network control is given by several authors [D90, LJY99, W92]. Neural networks have been applied to aircraft control problems by several researchers [BB96, Ha95, NK95, NNNC95, RS93, RC98, SWN98, TGM93], including the application to helicopter control [LCP97] and spacecraft attitude control [D97]. Neural networks have also been applied to the control of multiple robotic vehicles [FGW89]. The stability of neural network controllers is discussed in several papers [CK92, CL94, RC94, Sa93, Sa91].

[BB96] Balakrishnan and Biega, "Adaptive-Critic-Based Neural Networks for Aircraft Optimal Control"

Key Words: Neural Network Control, Aircraft Optimal Control, Perceptron, Adaptive

[CK92] Chen and Khalil, "Adaptive Control of Nonlinear Systems using Neural Networks"

Key Words: Neural Networks, Control, Stability

[CL94] Chen and Liu, "Adaptively Controlling Nonlinear Continuous-Time Systems using Multilayer Neural Networks"

Key Words: Neural Networks, Control, Stability

[D97] Dracopoulos, *Evolutionary Learning Algorithms for Neural Adaptive Control*

Key Words: Neural Network Control, Learning, Training, Spacecraft Attitude Control

[D90] Dreyfus, "Artificial Neural Network, Back Propagation, and the Kelley-Bryson Gradient Procedure"

Key Words: Neural Network Control, Back Propagation, Multi-layer Networks, Optimal Control

[FGW89] Fox, Gurewitz, and Wong, "A Neural Network Approach to Multi-Vehicle Navigation"

Key Words: Neural Networks, Multi-Vehicle Control, Path Planning

[Ha95] Ha, "Neural Networks Approach to AIAA Aircraft Control Design Challenge"

Key Words: Neural Network Control, Aircraft, Three Layer Feedforward Network

[KC97] Kim and Calise, "Nonlinear Flight Control Using Neural Networks"

Key Words: Neural Network Control, Aircraft,

[KMD92] Kraft, Miller, and Dietz, "Development and Application of CMAC Neural Network-Based Control"

Key Words: Neural Network Control, CMAC

[LCP97] Leitner, Calise, and Prasad, "Analysis of Adaptive Neural Networks for Helicopter Flight Control"

Key Words: Neural Network Control, Helicopter Flight Control

[LJY99] Lewis, Jagannathan, and Yesildirek, *Neural Network Control of Robot Manipulators and Nonlinear Systems*

Key Words: Neural Network Control, Theorems, Definitions, Applications

[NK95] Napolitano and Kincheloe, “On-Line Learning Neural-Network Controllers for Autopilot Systems”

Key Words: Neural Network Controller, Autopilot, Aircraft, Back-Propagation Algorithm

[NNNC95] Napolitano, Naylor, Neppach, and Casdorph, “On-Line Learning Nonlinear Direct Neurocontrollers for Restructurable Control Systems”

Key Words: Neural Network Control, Aircraft, back-propagation algorithm, combat maneuvers

[N92] Narendra, “Adaptive Control of Dynamical Systems using Neural Networks”

Key Words: Neural Network Control, Adaptive Control

[RS93] Rokhsaz and Steck, “Use of Neural Networks in Control of High-Alpha Maneuvers”

Key Words: Neural Network Control, Aircraft Control, High-Alpha Maneuver

[RC94] Rovithakis and Christodoulou, “Adaptive Control of Unknown Plants using Dynamical Neural Networks”

Key Words: Neural Network Control, Stability

[RC98] Rysdyk and Calise, “Fault Tolerant Flight Control via Adaptive Neural Network Augmentation”

Key Words: Neural Networks, Flight Control, Fault Tolerance, XV-15 Tiltrotor Aircraft

[Sa93] Sadegh, “A Perceptron Network for Functional Identification and Control of Nonlinear Systems”

Key Words: Neural Network Control, Stability

[Sa91] Sanner and Slotine, “Stable Adaptive Control and Recursive Identification using Radial Gaussian Networks”

Key Words: Neural Networks, Control, Stability

[SWN98] Smith, Ward, and Nguyen, “An Improved Artificial Neural Network Flight Mode Interpreter”

Key Words: Neural Network Control, Aircraft Flight Modes

[TGM93] Troudet, Garg, and Merrill, “Neurocontrol Design and Analysis for a Multivariable Aircraft Control Problem”

Key Words: Neural Network Control, Aircraft Control, Model Following Controller, H-Infinity

[W92] Werbos, “Neurocontrol and Supervised Learning: An Overview and Evaluation”

Key Words: Neural Network Control

2.9 Fuzzy Logic Control Systems

2.9.1 Theory of Fuzzy Logic Control Systems

Fuzzy logic [Z73] is a mathematical model that allows computers and analytical processes to account for the vagueness (fuzziness) in concepts; fuzzy logic is designed to reflect one of the ways that humans think. Fuzzy logic control was derived to combine the structure of conventional automatic control with the knowledge base of humans or experts, as shown in Figure 15. Knowledge is retained in a rule base. Even when a process is complicated and modeling the process is too difficult or too

costly, a fuzzy logic controller can be employed. Using only the knowledge of an experienced process operator, a fuzzy logic controller can be derived [Ka97].

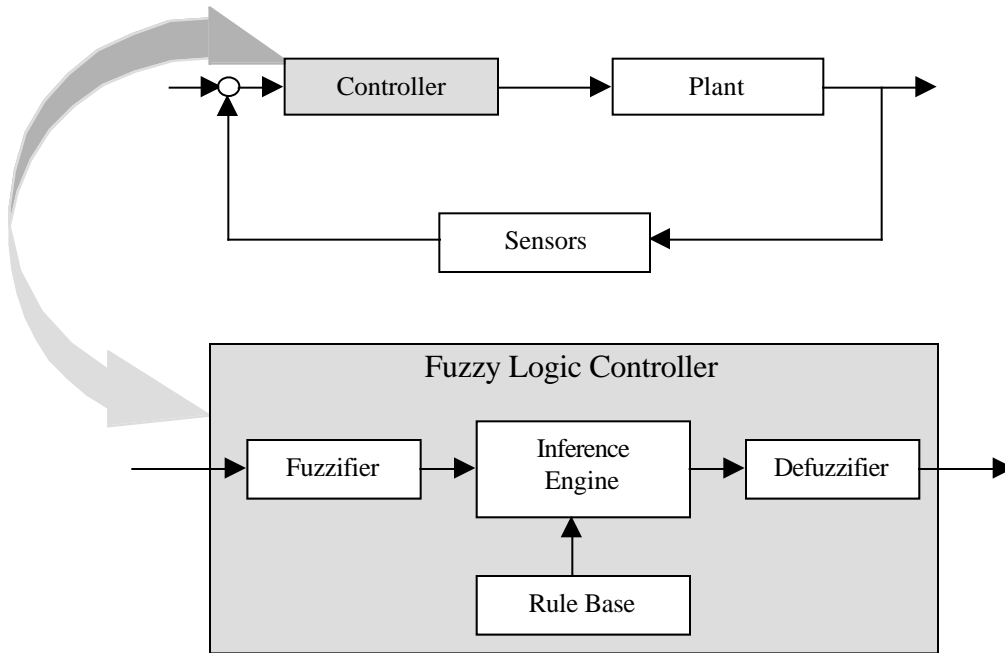


Figure 15. General framework for a fuzzy logic controller within a conventional closed loop system.

A fuzzy logic controller consists of three components: a fuzzifier, an inference engine (with a rule base), and a defuzzifier. The fuzzifier maps input variables into fuzzy sets. The fuzzy sets are created by the control system designer to aid in the reasoning about control actions given conditions expressed in terms of fuzzy sets. Membership functions defined on the continuous interval $[0,1]$ are used to define fuzzy sets. The rule base contains a set of n independent rules that are of the form:

If <Condition 1> Then <Action 1>
 If <Condition 2> Then <Action 2>
 ...
 If <Condition n > Then <Action n >.

Here, the fuzzy logic conditions are composed of fuzzy set variables and fuzzy logic operators (and, or, not), and the action is generally a control setting. The inference engine combines all of the applicable rules for a given set of input conditions and produces a final fuzzy set output. The defuzzifier maps the fuzzy set output of the inference engine into a continuous state output for the fuzzy logic controller.

2.9.2 Literature in Fuzzy Logic Control Systems

Fuzzy logic control was originally reported by Mamdani in 1974 [M74]. Several review papers and survey papers have been written on fuzzy logic control [L90a, L90b, LB92, To77, To85, S85]. A critique of the success of fuzzy logic control has been performed in the *IEEE Expert: Intelligent Systems and Their Applications* [IEEE94]. Stability issues related to fuzzy logic controllers and investigated by several researchers [Ber93, CRG96, LT90, LTD97, RM84, RV99]. Fuzzy logic control

is considered to be in a very mature state, with many successful applications in industry and a strong theoretical foundation from academe.

Fuzzy logic has been applied to the control of many systems. An application of fuzzy logic control for the guidance of aircraft, missiles, and spacecraft [FWNG98, GM97, KGSZ95, L84, L85, NA98, St93, SW98] and for the space shuttle attitude control has been performed [BL93, Kn93]. Fuzzy logic has also been applied to the runway balancing problem for NASA's FAST system [M99, MR98, RDI97].

[Ber93] Berenji, "Fuzzy and Neural Control"

Key Words: Fuzzy Logic Control, Neural Networks

[BL93] Berenji, Lea, Jani, *et al*, "Space Shuttle Attitude Control by Reinforcement Learning and Fuzzy Logic"

Key Words: Fuzzy Logic Control, Space Shuttle Application, Attitude Control

[CRF] Cao, Rees, and Feng., "Stability Analysis of Fuzzy Control Systems"

Key Words: Fuzzy Logic Control, Stability

[FWNG98] Fujimori, Wu, et al, "A Design of ALFLEX Flight Control System using Fuzzy Gain-Scheduling"

Key Words: Fuzzy Logic Control, Gain-Scheduling, Aerospace Vehicle

[GM97] Geng and McCullough, "Missile Control Using Fuzzy Cerebellar Model Arithmetic Computer Neural Networks"

Key Words: Fuzzy Logic Control, Missile Guidance Control, CMAC

[IEEE94] *IEEE Expert: Intelligent Systems, and Their Applications*, Issue: "A Fuzzy Logic Symposium"

Key Words: Fuzzy Logic Control, Panel of Experts, Critique

[Ka97] Kacprzyk, *Multistage Fuzzy Control*

Key Words: Fuzzy Logic Control, Multi-Stage Control, Applications

[Kn93] Knapp, *Fuzzy Based Attitude Controller for Flexible Spacecraft with On/Off Thrusters*

Key Words: Fuzzy Logic Control, Space Shuttle, Attitude Control

[KGSZ95] KrishnaKumar, Gonsalves, et al, "Hybrid Fuzzy Logic Flight Controller Synthesis via Pilot Modeling"

Key Words: Fuzzy Logic Control, Aircraft Control

[LB92] Langari and Berenji, "Fuzzy Logic in Control Engineering"

Key Words: Fuzzy Control, Survey

[LT90] Langari and Tomizuka, "Stability of Fuzzy Linguistic Control Systems"

Key Words: Fuzzy Logic Control, Stability, Theorems

[L84] Larkin, "A Fuzzy Logic Controller for Aircraft Flight Control"

Key Words: Fuzzy Logic Control, Aircraft Flight Control, ILS Approaches

[L85] Larkin, "A Fuzzy Logic Controller for Aircraft Flight Control"

Key Words: Fuzzy Logic Control, Aircraft Flight Control, ILS Approaches

[L90a] Lee, "Fuzzy Logic in Control Systems: Fuzzy Logic Controller – Part I"

Key Words: Fuzzy Control, Survey

[L90b] Lee, “Fuzzy Logic in Control Systems: Fuzzy Logic Controller – Part II”

Key Words: Fuzzy Control, Survey

[LTD97] Li, Turksen, Davison, and Smith, “Stabilization of Unstable and Unintuitive Plants by Fuzzy Control”

Key Words: Fuzzy Logic Control, Stability

[LM97] Lin and Maa, “Flight Control System Design by Self-Organizing Fuzzy Logic Controller”

Key Words: Fuzzy Logic Control, Aircraft, Flight Control

[M74] Mamdani, “Applications of Fuzzy Algorithms for Control of Simple Dynamic Plant”

Key Words: Fuzzy Control, Original Concept Paper

[M99] Mueller, “Statistical Performance Analysis Simulation of the FAST Merging Procedure Fuzzy Logic”

Key Words: Fuzzy Logic, pFAST, CTAS, Control

[MR98] Mueller, and Robinson, “Final Approach Spacing Tool (FAST) Velocity Accuracy Performance Analysis”

Key Words: Fuzzy Logic, FAST, CTAS, Control

[NA98] Nho and Agarwal, “Automatic Landing System Design Using Fuzzy Logic”

Key Words: Fuzzy Logic Control, Aircraft Control, Landing

[To77] Tong, “A Control Engineering Review of Fuzzy Systems”

Key Words: Fuzzy Logic, Review

[To85] Tong, “An Annotated Bibliography of Fuzzy Control”

Key Words: Fuzzy Control, Survey

[RM84] Ray and Majumder, “Application of Circle Criteria for Stability Analysis of Linear SISO and MIMO Systems Associated with Fuzzy Logic Controller”

Key Words: Fuzzy Logic Control, Stability

[RDI97] Robinson, Davis, and Isaacson, “Fuzzy Reasoning-Based Sequencing of Arrival Aircraft in the Terminal Area”

Key Words: Fuzzy Logic, FAST, Sequencing and Scheduling

[RV99] Rufus and Vachtsevanos, “Robust Stability of Mode-to-Mode Fuzzy Controllers”

Key Words: Fuzzy Logic, Stability, Lyapunov, Modes

[SW98] Sasiadek and Wang, “3-D Guidance and Navigation of Mobile and Flying Robot Using Fuzzy Logic”

Key Words: Fuzzy Logic Controller, Guidance, 3D Navigation, Mobile Robot, Flying Robot

[St93] Steinberg, “Development and Simulation of an F/A-18 Fuzzy Logic Automatic Carrier Landing System”

Key Words: Fuzzy Logic Control, Aircraft Carrier Landing Application

[S85] Sugeno, “An Introductory Survey of Fuzzy Control”

Key Words: Fuzzy Control, Survey

[Z73] Zadeh, “Outline of a New Approach to the Analysis of Complex Systems and Decision Processes”

Key Words: Fuzzy Logic, Linguistic Variables, Fuzzy Algorithms

2.10 Expert and Knowledge-Based Control Systems

2.10.1 Theory of Expert Systems and Knowledge-Based Systems used for Control

Expert systems or knowledge-based systems are used for the control of dynamical systems in a similar way that fuzzy logic control systems are implemented. As shown in Figure 16, an expert system can be located in the traditional location of a closed loop controller. The only difference between the expert system and the fuzzy logic control system is that the expert system controller does not include a fuzzifier and defuzzifier. Also, the expert system does not reason with fuzzy variables; rather, the expert system reasons about state variables and domain knowledge in the continuous time domain. Knowledge-based systems are very good at reasoning with rules that apply to a specific application domain, for instance, the Federal Air Regulations (FAR) for flight control. The Pilot's Associate is a well known example of an expert system for flight control [K87].

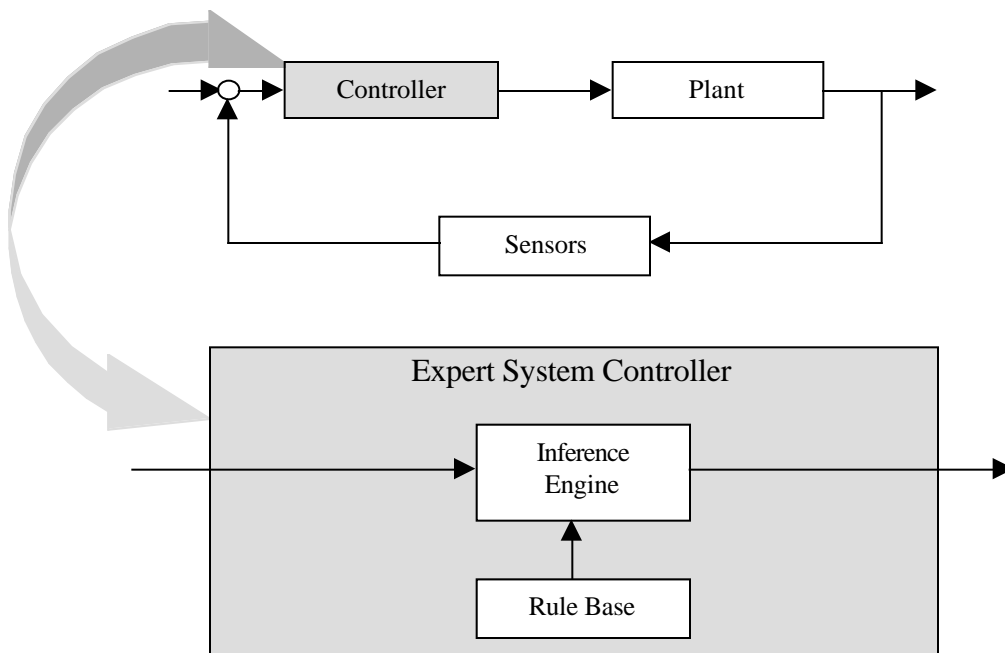


Figure 16. General framework for an expert system controller within a conventional closed loop system.

2.10.2 Literature in Expert Systems Control

Expert systems have been used in the control of aircraft by several researchers [BS93, Cr83, CWC85, JLN99, K87, MD90, MG90, O95, PJ84] as well as for helicopter control [GW87]. Additionally, 3D motion control for underwater vehicles [BC86] and mobile robots [WSK86] have also been designed. Theory of the stability of expert control systems is discussed in [PL93, PL96] and methods to verify the completeness of a rule set are in [G88, LP95, NPLP85, NPLP87, PSB92, SSS82]. Real-time issues and a survey of applications are discussed in [LCS88].

[AA93] Astrom and Arzen, "Expert Control"

Key Words: Expert Systems, Control, Fuzzy Logic Control

[BS93] Belkin and Stengel, "AUTOCREW: A Paradigm for Intelligent Flight Control"

Key Words: Expert Systems, Aircraft Control

[BC86] Blidberg and Chappel, "Guidance and Control Architecture for the EAVE Vehicle"

Key Words: Knowledge Based System, Hierarchical Control, UAV, 3D Navigation

[CWC85] Clema, Werling, and Chande, "Expert Systems for Real Time Applications"

Key Words: Expert System Control, Real Time, EMULAR Architecture, Pilot Decision Making

[Cr83] Cross, *Qualitative Reasoning in an Expert System Framework*

Key Words: Expert Systems, Aircraft Control, ATC, Qualitative Reasoning

[GW87] Garvey and Wesley, "Knowledge-Based Helicopter Route-Planning"

Key Words: Knowledge-Based System, Helicopter Control, Dynamic Programming, Flight Planning

[G88] Ginsberg, "Knowledge-Base Reduction: A New Approach to Checking Knowledge-Bases for Inconsistency and Redundancy"

Key Words: Knowledge-Base Systems, Verification and Validation

[H89] Handelmann, *A Rule-Based Paradigm for Intelligent Adaptive Flight Control*

Key Words: Expert system, Intelligent Flight Control, Aircraft

[HS89] Handelmann and Stengel, "Combining Expert System and Analytical Redundancy Concepts for Fault Tolerance Flight Control"

Key Words: Expert System, Aircraft, Fault Tolerance, Flight Control

[JLN99] Jones, Laird, Nielsen, *et al*, "Automated Intelligent Pilots for Combat Flight Simulation"

Key Words: Expert Systems, Flight Control

[K87] Key, "Cooperative Planning in the Pilot's Associate"

Key Words: Pilot's Associate, Expert Systems, Route Planning

[LCS88] Laffey, Cox, Schmidt, Kao, and Read, "Real-Time Knowledge-Based Systems"

Key Words: Knowledge-Based Systems, Real-Time Control, Survey, Aerospace

[LP95] Lunardhi and Passino, "Verification of Qualitative Properties of Rule-Based Expert Systems"

Key Words: Expert Systems Control, Stability, Verification and Validation

[MD90] McIngvale and Dudley, "Expert System Technology Applied to the Automatic Control of Multiple Unmanned Aerial Vehicles"

Key Words: Expert System Control, Multiple Vehicles, Aircraft

[MG90] McManus and Goodrich, "Artificial Intelligence (AI) Based Tactical Guidance for Fighter Aircraft"

Key Words: Knowledge-Based System, Tactical Decision Generator, Aircraft Control

[NPLP85] Nguyen, Perkins, *et al*, "Checking an Expert Systems Knowledge Base for Consistency and Completeness"

Key Words: Expert Systems, Knowledge Based System, Verification, Rule Sets

[NPLP87] Nguyen, Perkins, Laffey, and Pecora, "Knowledge-Base Verification"

Key Words: Expert Systems, Knowledge Based System, Verification, Rule Sets

[O95] Onken, "Functional Development and Field Test of CASSY – A Knowledge-Based Cockpit Assistant System"

Key Words: Knowledge-Based System, Aircraft Control, Cockpit Assistant, Hierarchical System

[PJ84] Pisano and Jones, "An Expert Systems Approach to Adaptive Tactical Navigation"

Key Words: Expert Systems, Navigation, Aircraft Domain

[PL96] Passino and Lunardhi, "Qualitative Analysis of Expert Control Systems"

Key Words: Expert Systems Control, Stability

[PL93] Passino and Lunardhi, "Stability Analysis of Expert Control Systems"

Key Words: Expert Systems Control, Stability Analysis

[PSB92] Preece, Shinghal, and Batarekh, "Principles and Practice in Verifying Rule-Based Systems"

Key Words: Rule-Based Systems, Verification and Validation

[SSS82] Suwa, Scott, and Shortliffe, "An Approach to Verifying Completeness and Consistency in a Rule-Based Expert System"

Key Words: Expert System, Rule Set, Completeness

[WSK86] Weisbin, de Saussure, and Kammer, "A Real-Time Expert System for Control of an Autonomous Mobile Robot Including Diagnosis of Unexpected Occurrences"

Key Words: Expert System, Control, Mobile Robot

2.11 Airspace Complexity, Dynamic Density, and Chaos

2.11.1 Discussion

As stated by the RTCA Select Committee on Free Flight [RTCA95]:

Dynamic density is described as the "essential factor affecting conflict rate in both the en route and terminal airspace." These factors are traffic density, complexity of flow, and separation standards.

In several investigations on dynamic density, the relative importance of factors effecting dynamic density were determined. These investigations typically determine dynamic density as a linear combination of weighted factors. However, the literature do not report any single agreed upon model for dynamic density.

As investigated in a Wyndemere study [An96], Table 2 identifies important factors that affect the complexity of the air traffic situation and the parameters that rank the highest. In addition to a ranking, the study (performed for NASA's AATT program) determined a linear combination of these factors to establish a measure for dynamic density. The definitions of these factors and the coefficients of this dynamic density function are useful for our investigation. We do not expect that the entire list of factors in Table 2 are needed for a dynamic density definition, so the relative weightings and the rankings in Table 2 help us determine a simple definition for dynamic density to use in this investigation.

Table 2. Factors contributing to airspace complexity [An96].

Complexity Factor	Ranking *
Level of Knowledge of Intent	7.9
Density of Aircraft	7.2
Number of Crossing Altitude Profiles	7.2
Proximity of Neighboring Aircraft	6.7
Coordination level of effort	6.7
Points of Closest Approach Distribution	6.5
Number of Aircraft Climbing and Descending	6.4
Separation Requirements	6.3
Proximity of Potential Conflicts to Sector Boundary	6.0
Angle of Convergence in a Conflict Situation	6.0
Complexity of the Airspace Structure	5.2
Variance in Directions of Flight of all Aircraft	5.1
Mixture in Performance of all Aircraft	5.1
Number of Facilities servicing a given Airspace Region	5.0
Variance in Aircraft Speed for all Aircraft	4.3
Presence and Operation of SUA in the Airspace	3.9
Weather Effects on Aircraft Density	3.2

* Ranking on 0 – 10 scale with 0 for low importance and 10 for high importance.

In a NASA study [LSBB98], similar linear combinations were used to build a linear model for dynamic density. The dynamic density measure in the NASA study included a linear combination of the factors listed in Table 3.

Table 3. Factors contributing to traffic complexity [LSBB98].

Complexity Factor	Ranking *
Heading Changes	2.17
Conflict Predicted from 25 nmi to 40 nmi	1.85
Conflict Predicted from 40 nmi to 70 nmi	1.85
Minimum Distance from 5 nmi to 10 nmi	1.18
Minimum Distance from 0 nmi to 5 nmi	1.02
Altitude Changes	0.88
Traffic Density	0.79

* A multiple regression weighting analysis with lower weights indicating less significance.

Further work on dynamic density suggests that in addition to how hard the complex problem looks (as measured by factors such as in Table 2 and Table 3), how hard a complex problem is to solve is also important for a dynamic density measurement. The number of maneuvers available to ATC to resolve a conflict represents a component of dynamic density that is added by this method.

Airspace complexity may also include proximity to storm cells or terrain, but these are not usually included in dynamic density measurements.

Dynamic density values can range from small to large with different effects on stability and performance. In our study, we investigate different dynamic density levels to observe any affect the proposed distributed control technique has as a function of dynamic density [N98].. In the worst case, where dynamic density is very high, chaos may set in. Because of this, a brief description of chaos is given and how it relates to the ATC problem.

2.11.2 Literature in Airspace Complexity, Dynamic Density, and Chaos

Several studies have been performed to understand airspace complexity and workload issues [An96, LSBB98, MMG94, PB96, SSKH98]. A review of the literature for airspace complexity appears in [MGMK95, RMM97]. Chaos theory as it relates to dynamic systems is explained in several texts, e.g., [ASY96, Wi97]. An overview of stability of dynamical systems and chaos is covered by [PS90].

[An96] Anonymous, *An Evaluation of Air Traffic Control Complexity*

Key Words: Airspace Complexity, Dynamic Density, ATC, conflict detection, Workload

[ASY96] Alligood, Sauer, and Yorke, *Chaos: An Introduction to Dynamical Systems*

Key Words: Chaos Theory, Dynamical Systems

[DP00] Delahaye and Puechmorel, "Air Traffic Complexity: Towards Intrinsic Metrics"

Key Words: Dynamic Density, Entropy, geometric complexity, ATC, CD&R

[LSBB98] Laudeman, Shelden, Branstrom, and Brasil, *Dynamic Density: An Air Traffic Management Metric*

Key Words: Dynamic Density, Traffic Complexity, Human Factors, ATM, Workload

[MGMK95] Mogford, Guttman, Morrow, and Kopardekar, *The Complexity Construct in Air Traffic Control: A Review and Synthesis of the Literature*

Key Words: ATC, Complexity, Literature Review

[MMG94] Mogford, Murphy, and Guttman, "Using Knowledge Exploration Tools to Study Airspace Complexity in Air Traffic Control"

Key Words: Airspace Complexity

[N98] Niedringhaus, "Solution Complexity Measure"

Key Words: Complexity, ATC, Dynamic Density, conflict resolution

[PB96] Pawlak, Brinton, Crouch, and Lancaster, "A Framework for Evaluation of Air Traffic Control Complexity"

Key Words: Airspace Complexity, Dynamic Density, ATC, conflict detection, Workload

[PS90] Pradeep and Shrivastava, "Stability of Dynamical Systems: An Overview"

Key Words: Stability, Historical Survey, Lyapunov Stability, Chaos

[RTCA95] RTCA, *Report of the RTCA Board of Directors' Select Committee on Free Flight*

Key Words: Free Flight, RTCA, Concept of Operations

[RMM97] Rodgers, Mogford, and Mogford, "The Relationship of Sector Characteristics to Operational Errors"

Key Words: Airspace Complexity, Review of Literature, Operational Errors, Human Factors

[SSKH98] Smith, Scallen, Knecht, and Hancock, "An Index of Dynamic Density"

Key Words: Dynamic Density, Conflict Detection, Free Flight

[SSG98] Sridhar, Sheth, and Grabbe, "Airspace Complexity and its Application in Air Traffic Management"

Key Words: Airspace Complexity, Dynamic Density, ATM, Workload

[Wi97] Williams, *Chaos Theory Tamed*

Key Words: Chaos Theory

2.12 Alerting Logic

2.12.1 Discussion

Alerting logic is related to when and what type of conflict detection alert should be given to the pilot or air traffic controller. For *Free Flight* [RTCA95] outside of congested airspace, an aircraft will be allowed to fly autonomously as long as no other traffic crosses an *Alert Zone* around the aircraft, as shown in Figure 17. If the Alert Zone is violated, either 1) an air traffic controller will intervene to assist in conflict avoidance, or 2) the flight crews will resolve the conflict autonomously while being monitored by the ATM system. The size and shape of the Alert Zone was investigated in [KMH96, KP97a, KP97b]. To ensure safety, no aircraft should penetrate another aircraft's *Protected Airspace Zone*. The Protected Airspace Zone is defined by horizontal and vertical separation requirements.

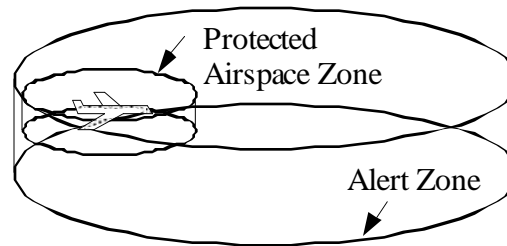


Figure 17. Free Flight zones around aircraft.

The work of Kuchar [KH95, Ku96] presents a unified methodology to alerting logic. Figure 18 illustrates the logic for a single-stage and two-stage alerting logic. For conflict detection between aircraft, the conflict can occur at the Alert Zone in a single-stage alert, or a caution can be established before the Alert Zone conflict. Multi-stage alerts, as designed by the RTCA ADS-B based conflict detection and resolution operational concept, allows warnings to alert as the severity of the situation gets worse, as shown in Figure. In Figure, low, medium, high, and critical alerts trigger at closer ranges.

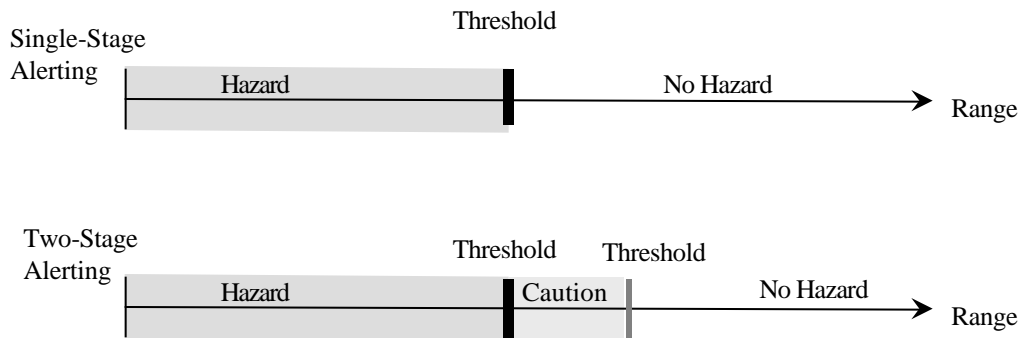


Figure 18. Single-stage alerting logic and two-stage alerting logic.

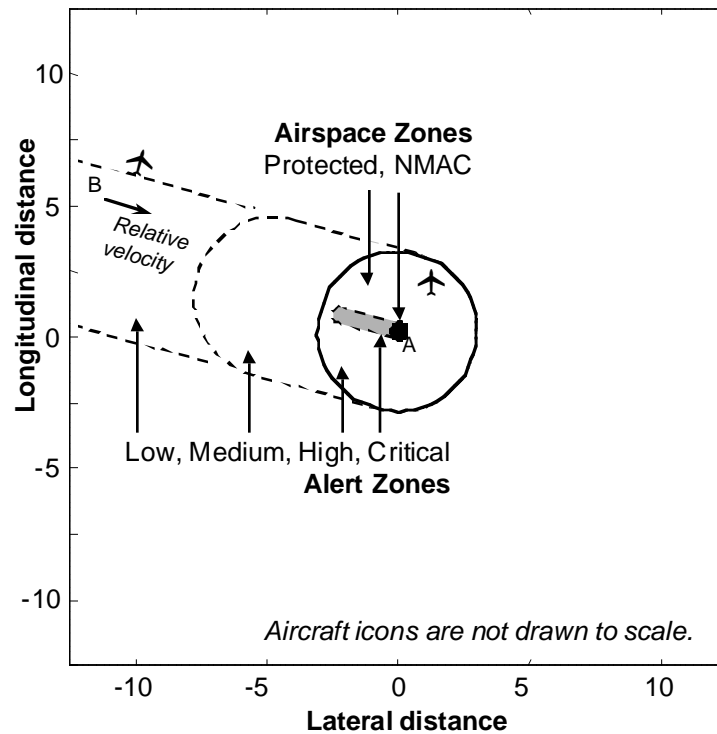


Figure 19. Multi-stage Protected Airspace Zone alerting logic allowing for low, medium, high, and critical alerts.

Conflict scenarios can be divided into two categories: tactical and strategic. Tactical scenarios are near-range conflicts which cannot be avoided without immediate action. Strategic scenarios are long-range conflicts which can be smoothly resolved so that they never become near-range threats. In this research, we assume that only strategic maneuvers are performed in the DAG TS operational concept.

Conflict scenarios can also incorporate cooperative aircraft as well as non-cooperative aircraft. That is, the intruder aircraft may cooperatively maneuver to assist in increasing the miss distance, may be non-cooperative and execute no maneuver or may blunder and execute a maneuver that reduces the miss distance. We investigate both cooperative maneuvers and non-cooperative cases where no blundering occurs. This implicitly assumes that the Alert Zone size and shape will provide a sufficient safety factor to account for the blundering intruder aircraft. For the non-cooperative case, we assume that the intruder has a constant-velocity vector. For conflict detection analysis in this report, we assume that wind conditions are the same for both aircraft, even though in strategic cases, this is a poor assumption.

Three fundamental controls for maneuvers can be used (alone or in combination) to avoid a conflict:

- turn (horizontal maneuvers),
- accelerate/decelerate (speed control maneuvers), and
- climb/descend (vertical maneuvers).

Because vertical separation minimums are significantly less (currently by a factor of 15 for en route flight) than horizontal minimums, vertical maneuvers fare better when the basis of comparison is not

absolute separation, but separation relative to the appropriate Protected Airspace Zone minimum. Of course, separation resulting from both turns and vertical maneuvers depend on the maneuver rates (lateral acceleration and altitude rate, respectively). Speed control provides the least separation over a given time span of the three maneuver types. For further information on conflict detection and resolution maneuvers, we refer the reader to [KP97a] which includes a complete analysis of conflict resolution strategies by considering all three control options. Kuchar and Yang [KY97] provide a survey of the literature for conflict detection and resolution algorithms.

In the research into decentralized control techniques for DAG TS, the particular method of conflict detection and resolution is not as important as the fact that some conflict detection and resolution algorithm takes action. The number of conflicts and coordination of conflicts are important features of the research more than the type of conflict detection and resolution maneuvers used.

2.12.2 Literature in Alerting Logic

Several methods of alerting logic are applicable to the ATC situation. A review of methods for conflict detection and resolution has recently been published by Kuchar and Yang [KY97] and for potential field methods by Zeghal [ZE98]. Others appear here, but a detailed survey of conflict detection and resolution algorithms has not been performed.

[AH97] Andrews and Hollister, "Impact of Intent-Based Maneuver Constraints on Alert Rates"
Key Words: Free Flight, Conflict Alert, CD&R, Intent

[BSL00] Bilimoria, Sheth, et al, "Performance Evaluation of Airborne Separation Assurance for Free Flight"
Key Words: Free Flight, CD&R, Geometric Optimization, Safety, Efficiency, Stability

[DAC96] Durrand, Alliot, and Chansou, "Optimal Resolution of En Route Conflicts"
Key Words: Free Flight, CD&R, Multiple Aircraft Conflicts, Genetic Algorithms

[Eb94] Eby, "A Self-Organizational Approach for Resolving Air Traffic Conflicts"
Key Words: Free Flight, Separation Assurance, Potential Fields, CD&R

[Eb99] Eby and Kelly, "Free Flight Separation Assurance Using Distributed Algorithms"
Key Words: Free Flight, Separation Assurance, Potential Fields, CD&R

[KMH96] Krozel, Mueller, and Hunter, "Free Flight Conflict Detection and Resolution Analysis"
Key Words: Free Flight, CD&R, Tactical, Strategic, Alert Zones

[KP97a] Krozel, and Peters, "Conflict Detection and Resolution for Free Flight"
Key Words: Free Flight, CD&R, Tactical, Strategic, Alert Zones

[KP97b] Krozel, and Peters, "Strategic Conflict Detection and Resolution for Free Flight"
Key Words: Free Flight, CD&R, Strategic, Alert Zones, Cost Benefits

[KPB00] Krozel, Peters, and Bilimoria, "A Decentralized Control Strategy for Distributed Air/Ground Traffic Separation"
Key Words: Free Flight, CD&R, Strategic, Alert Zones, Separation Assurance, Distributed Control, DAG-TM

[Ku96] Kuchar, "Methodology for Alerting-System Performance Evaluation", and Dynamics, , 1996.
Key Words: Hazard Alerting, TCAS, SOC Curves

[KH95] Kuchar and Hansman, *A Unified Methodology for the Evaluation of Hazard Alerting Systems*
Key Words: Hazard Alerting, TCAS, SOC Curves

[KY97] Kuchar and Yang, “Survey of Conflict Detection and Resolution Modeling Methods”

Key Words: Conflict Detection and Resolution, Survey

[Me98] Meckiff, “Conflict Resolution Support for Random Routing”

Key Words: Free Flight, CD&R, Uncertainties

[MSS97] Menon, Sweriduk, and Sridhar, “Optimal Strategies for Free Flight Air Traffic Conflict Resolution”

Key Words: Free Flight, CD&R, Optimal Control, Multiple Aircraft Conflicts

[P98] Paielli, “Empirical Test of Conflict Probability Estimation”

Key Words: Free Flight, Conflict Detection and Resolution, Probability

[PE97] Paielli and Erzberger, “Conflict Probability Estimation for Free Flight”

Key Words: Free Flight, Conflict Detection and Resolution, Safety, Probability

[PE99] Paielli and Erzberger, “Conflict Probability Estimation Generalized to Non-Level Flight”

Key Words: Free Flight, Conflict Detection and Resolution, Safety, Probability

[YK98] Yang and Kuchar, “Using Intent Information in Probabilistic Conflict Analysis”

Key Words: Free Flight, CD&R, Intent Information, Probabilistic

[Ze98] Zeghal, “A Review of Different Approaches Based on Force Fields for Airborne Conflict Resolution”

Key Words: Free Flight, CD&R, Literature Review, Potential Fields

3.0 TRADE-OFF STUDY

This chapter presents a trade-off analysis of the leading techniques for decentralized/distributed control.

3.1 DAG TS Functional Design Requirements

To define the functional requirements of DAG TS, we refer to the DAG TM concept of operations document developed by the DAG TM Team [DAG99]. The vision statement for DAG TM is [DAG99]:

“Distributed Air/Ground Traffic Management is a National Airspace System concept in which flight deck (FD) crews, air traffic service providers (ATSP) and aeronautical operational control (AOC) facilities use distributed decision-making to enable user preferences and increase system capacity, while meeting air traffic management requirements. DAG-TM will be accomplished with a human-centered operational paradigm enabled by procedural and technological innovations. These innovations include automation aids, information sharing and Communication, Navigation, and Surveillance (CNS) / Air Traffic Management (ATM) technologies.”

This vision statement identifies the following functional requirements:

- System must provide for Distributed Decision Making
- System must Enable User Preferences
- System must Increase System Capacity while maintaining System Safety
- System must Meet ATM Requirements
- System must be Human-Centered

Further requirements from the DAG TM concept of operation document include:

- System should address all user classes (including Commercial, Business Jets, General Aviation, Military, and Helicopters)
- System must cover all flight phases
- System must operate with the minimum equipage being the same as that required to operate the current ATC system, and that a spectrum of equipage levels will exist.

From these DAG TM requirements, we consider all these requirements relevant to DAG TS, with the exception of the requirement that DAG TM cover all flight phases. In the DAG TS research of this report, we focus on the en route phase of flight.

3.2 Trade-Off Features

The most applicable techniques from the survey are compared based on the following criteria:

- Ability of the Theory to meet the Functional Requirements of DAG TS
- Maturity of the Theory and Evidence of Theorems which address System Stability
- Evidence that the Theory has been applied to ATM or a similar system
- Evolutionary and Scaling Properties to Accommodate NAS growth
- Economical Impact of Implementing the Technique

Trade-off matrices are created and filled to rank approaches on these criteria. The theories that rank highest in satisfying these criteria are discussed in greater detail. From the top ranking approaches, one (or a combination of techniques) are selected. This selection is discussed in Chapter 4 where the modeling and simulation effort for the selected method is described.

3.2.1 Meeting DAG TS Functional Requirements

Section 3.1 defines the functional requirements of DAG TS. In the tradeoff study, we identify those requirements that a particular decentralized control method does not adequately address or is incapable of addressing adequately for DAG TS.

3.2.2 Maturity of Theory

Some of the methods for decentralized control have been researched for several years, and yet others are still in their nascent stages. With greater maturity comes both more mature applications that demonstrate the method but also provide for the time needed to research critical issues associated with the method, for instance, stability and completeness issues. Some of the theories behind the decentralized control methods offer stability theorems or proofs that provide, under often simplified or constrained conditions, evidence that the theory is mathematically sound.

3.2.3 Application to ATM/ATC

Some decentralized control methods have been applied to ATM or ATC. The lessons learned from these applications may provide additional support for the method to be applicable to the DAG TS problem domain. However, having a demonstrated application of the method in ATM/ATC is not necessarily weighted as heavily as having a thoroughly demonstrated application in one or more other domains.

3.2.4 Evolutionary and Scaling Properties

Another concern related to the applicability of a decentralized control approach is related to the future growth of the NAS. A viable technique must not become obsolete within a very short time. Evolutionary properties and scaling properties that accommodate the future growth of the NAS are noted for each method of decentralized control.

For instance, one of the many beneficial properties of distributed systems deals with scalability [N94]. A system is scalable if the system can accommodate the addition of vehicles (computers, resources) without suffering noticeable loss in performance (or increase in administrative complexity). Distributed control for ATC is scalable because the control system scales linearly with every aircraft (and thus, computer) that is added to the system.

As the system scales, it is not practical to expect that all vehicles are equipped the same, so the ATC system studied in this research is a heterogeneous system. Two methods of ensuring that a heterogeneous system evolves and scales within minimal problems is coherence through the use of common interfaces and the use of protocols. A coherent system requires that all computers in the system support a common interface. For example, all aircraft in a coherent ATC system might be required to support ADS-B as the common method of communication. Coherence can be achieved through a communications protocol as well. Using a communications protocol stipulates that regardless of the method of communication, the protocol defines the only message formats allowed for communication. For example, ADS-B has a message protocol and principled negotiation defines a communication protocol for stable communications that lead to compromises to conflicts.

Scalability encompasses three major factors:

1. Numerical – the number of aircraft serviced by ATM and/or number of ATM transactions (e.g., conflict resolutions)
2. Geographical – the average or total distance or area for which the system covers (e.g., density relative to a characteristic size like the separation standard), and
3. Administrative – complexity of the ATM control overseeing the system (e.g., hierarchy levels, number of sectors, or number of dynamic resectorizations).

These three factors provide numerical metrics for comparing decentralized control approaches.

3.2.5 Economical Impact

Each method for decentralized control requires some infrastructure to implement. The amount of infrastructure needed and the rough cost of implementation is noted for each method. If a method is too costly, then even if technically and operationally viable, it is not economically viable.

3.2.6 Comparison

Table 4 illustrates the comparison of the different decentralized control methods and the trade-offs.

Table 4. Comparison of decentralized control techniques.

	Meets	Maturity	ATM/ATC	Evolutionar	Economic	Stability	Notes *
--	-------	----------	---------	-------------	----------	-----------	---------

Control Technique	DAG TS Reqs	of Theory	Applications	y and Scaling Properties	al Impact	Theory	(see below)
Hierarchical Control	Yes	Mature	Demonstrated in Aircraft Flight Control and ATC	Good Limited Scalability	Infrastructure and Aircraft equipage	Limited Cases	-
Distributed Control	Yes	Mature	Demonstrated in ATC and Flight Control	Very Good	Infrastructure and Aircraft equipage	Limited Cases	-
Hybrid Control	Some Limitations	Nascent	Demonstrated in ATC and Flight Control	Good	Infrastructure and Aircraft equipage	Limited Cases	-
Control by Permission, Periodic Coord., Supervisory	Some Limitations	Growing	Demonstrated in Practice for ATM	Good Limited Scalability	Ground Infrastructure and Aircraft equipage	None	-
Collab. Decision Making	Some Limitations	Growing	Demonstrated in Practice for ATM	Good Limited Scalability	Minimal; Changes in Progress	None Reported	(1)
Principled Negotiation	Some Limitations	Growing	Several ATC Demonstrated Systems	Good	Ground Infrastructure and Aircraft equipage	Limited Cases	(2)
Behavior-Based Control	Some Limitations	Growing	Demonstrated for Robotics	Good	Aircraft equipage	None Reported	-
Neural Network Control	Some Limitations	Mature	Demonstrated for Aircraft Flight Control	Good	Depends on Use	Theory Applies	-
Fuzzy Logic Control	Some Limitations	Mature	Demonstrated for Aircraft Flight Control	Good	Depends on Use	Theory Applies	(3)
Expert System Control	Some Limitations	Growing	Demonstrated for Aircraft Flight Control	Good	Depends on Use	Some Cases	(3)

Notes: (1) Depends on roles and responsibilities assigned to humans-in-the-loop;

(2) Allows for user preferences and negotiation;

(3) Fuzzy logic control systems considered a superset of expert systems.

3.3 Down Select

There are several filters or issues that are investigated to down select the leading methods for decentralized control. Both quantitative and qualitative measures are appropriate.

Given the hierarchical nature of a supremal controller coordinating many local controllers, several of the methods are more applicable to the supremal control position while others are more applicable to the local control. In the following ranking, the entries in the trade-off matrix were used to order the applicable methods.

Supremal Control

- (1) Hierarchical Control
- (2) Distributed Control
- (3) Hybrid Control
- (4) Collaborative Decision Making
- (5) Supervisory and Control by Permission

Local Control

- (1) Principled Negotiation
- (2) Fuzzy Logic Control
- (3) Neural Network Control
- (4) Expert Systems Control
- (5) Behavior-Based Control

The order of these lists is important. Ranked highest is the most applicable method for decentralized control for a Free Flight environment. For supral control positions, hierarchical and distributed control techniques are very applicable. For local control, principled negotiation ranks the highest.

At this stage of the research, hierarchical and distributed control methods that coordinate principled negotiation strategies are further pursued and demonstrated in Chapters 3, 4, and 5.

4.0 DAG TS MODELING AND EVALUATION METHODOLOGY

This chapter presents the methodology for modeling and evaluating system performance and system stability for a decentralized control system for DAG TS operations.

4.1 System Performance

For system performance, efficiency and safety measures are specified. These measures mathematically define equations that integrate or sum local efficiency and safety measures into total system efficiency and safety measures.

4.1.1 Efficiency

Efficiency measures include deviations (or integrated deviations) from the nominal flight plan, on time performance with meeting the next one or two waypoints in an intent broadcast, fuel usage, or other measures. The efficiency measure used for this research is a Direct Operating Cost (DOC) measure that combines the difference between the distance traveled and the minimum distance traveled with the difference between the planned time and actual time.

A DOC penalty function generally incorporates both fuel and time elements. Included in the DOC equation are 1) the additional fuel required due to the increased drag and flight path distance traveled during a maneuver and 2) the additional (non-fuel) operating costs due to the additional time required to execute the maneuver and return back to course:

$$DOC = C_{fuel} W_{fuel} + C_{time} T \quad (4.1)$$

where C_{fuel} is the cost of fuel, W_{fuel} is the additional fuel used in the maneuver, C_{time} is the time dependent aircraft operating cost, and T is the additional time used in the maneuver. However, while meaningful numbers for fuel and time coefficients as well as fuel burn can be determined for individual aircraft, in this investigation, we are more concerned with general system properties. Therefore we simplify the DOC penalty function to be a function of path length exclusively:

$$DOC = \frac{S_{act} - S_{nom}}{S_{nom}}, \quad (4.2)$$

where the additional distance an aircraft travels is normalized by the nominal path distance between the two fixes. In this way, the change in DOC is represented in a percent deviation. Finally, a system efficiency measure is computed by averaging all the changes in DOC of the aircraft in the system. The total change in DOC for a system with N aircraft is:

$$DOC_{total} = \frac{1}{N} \sum_{i=1}^N DOC_i \quad (4.3)$$

These N aircraft include all aircraft that complete their flights across the reference airspace within a specified time. Sometimes we prefer to characterize reduced system performance as:

$$\text{Total DOC Reduction} = 1 - \frac{1}{N} \sum_{i=1}^N DOC_i \quad (4.4)$$

4.1.2 Safety

Safety measures are based on conflicts and potential conflicts. In order to model safety, we track neighboring aircraft (within a given radius around the ownship) and the proximity to neighbor aircraft. Points of closest approach are computed for all neighboring aircraft assuming a constant

velocity vector for all aircraft. There are two measures of safety that we keep track of for the performance metric. First, the number of actual conflicts are measured. An actual conflict is a separation violation, when two aircraft pass within R (e.g., 5 nmi) horizontally or within H (e.g., 1000 ft) vertically. Next, the number of conflict alerts are measured. Conflict alerts occur when a conflict is detected to occur within a given time horizon; in our test cases, a 8 minute time horizon is used.

The Point of Closest Approach (PCA) between aircraft i and aircraft j is computed as follows. Figure 19 show the geometry of two aircraft for this analysis. Assuming that all aircraft are flying with a constant velocity vector, we determine the vector location of the PCA as:

$$\vec{r}_{PCAij} = \hat{c}_{ij} (\vec{r}_{ij} \cdot \hat{c}_{ij}) \quad (4.5)$$

$$\vec{r}_{ij} = \vec{r}_i - \vec{r}_j \quad (4.6)$$

$$\hat{c}_{ij} = \frac{\vec{v}_i - \vec{v}_j}{\|\vec{v}_i - \vec{v}_j\|} \quad (4.7)$$

and the PCA distance as:

$$PCA_{ij} = \|\vec{r}_{PCAij}\| \quad (4.8)$$

where \vec{r}_i locates aircraft i with constant velocity \vec{v}_i and \vec{r}_j locates aircraft j with constant velocity \vec{v}_j . In order to determine if a conflict exists, we compute the time to PCA and trigger an alert if it is within the conflict alert time horizon. The time to PCA is defined for aircraft i and aircraft j as:

$$\tau_{ij} = -\frac{\vec{r}_{ij} \cdot \hat{c}_{ij}}{\|\hat{c}_{ij}\|}. \quad (4.9)$$

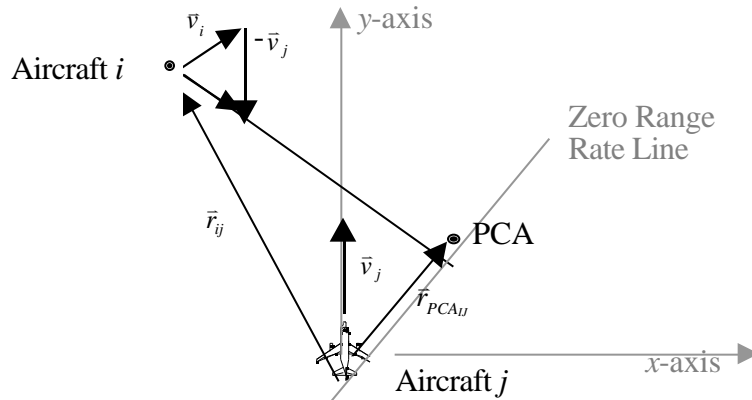


Figure 19. Relative motion geometry between two aircraft and the PCA.

4.1.3 Airspace Complexity

Airspace complexity is modeled using dynamic density as the key variable.. Measures for airspace complexity were included in the literature review of Chapter 2. The top ranking factors in determining dynamic density are as follows:

1. Level of Knowledge of Intent
2. Density of Aircraft
3. Number of Crossing Altitude Profiles
4. Proximity of Neighboring Aircraft

5. Coordination Level of Effort
6. Points of Closest Approach Distribution

Since we are performing this research for the en route airspace and we are assuming horizontal 2D scenarios for this effort, some of these factors do not apply. Furthermore, we assume that the intent of aircraft is broadcast to all aircraft, so the level of knowledge of intent is also not applicable. The end result is that we consider the following factors in our dynamic density measurement for airspace complexity:

1. Density of Aircraft, δ , the number of aircraft N per unit reference area A_{ref} (either a reference circle or square for mathematical studies or a reference sector area or center area for US operational ATM studies):

$$\delta = N / A_{ref} \quad (4.10)$$

distance between aircraft i and j):

$$\delta_{NN} = \frac{1}{N} \min_{i \neq j} \{d_{ij}\} \quad (4.11)$$

2. Points of Closest Approach Distribution, δ_{PCA} , the average PCA

$$\delta_{PCA} = \frac{1}{N} \sum_{i=1}^N PCA_{ij} \quad (4.12)$$

At the system level, we consider 3 potential dynamic density measurements, each being more complex than the previous:

$$D_1 = \delta \quad (4.13)$$

$$D_2 = c_1 \delta + c_2 \delta_{NN} \quad (4.14)$$

$$D_3 = c_1 \delta + c_2 \delta_{NN} + c_3 \delta_{PCA} \quad (4.15)$$

where the constants c_i are determined by the relative weights established in experimentation (such as the work performed by Wyndemere as discussed in Chapter 2). Next, we discuss several issues related to these dynamic density measurements.

The upper limit on density is determined by the most dense packing of circles in a plane. A hexagonal packing of the horizontal plane with circles produces a 90.7% covering, which is the optimal solution to the packing problem [KL00]. Figure 20 illustrates the optimal packing geometry. From the optimal packing, the maximum number of aircraft N_{max} protected by circles of radius R that all fit within a reference area A_{ref} is defined by:

$$\frac{N_{max} \pi R^2}{A_{ref}} = \frac{\pi}{2\sqrt{3}} = 0.907 \quad (4.16)$$

which determines N_{max} to be:

$$N_{max} = \frac{0.907 A_{ref}}{\pi R^2} \quad (4.17)$$

Furthermore, the upper limit on dynamic density would then be:

$$\delta_{\max} = \frac{N_{\max}}{A_{\text{ref}}} = \frac{0.907}{\pi R^2} \quad (4.18)$$

Unfortunately, the upper limit for density can only be achieved if all aircraft fly in the same direction with the same velocity.

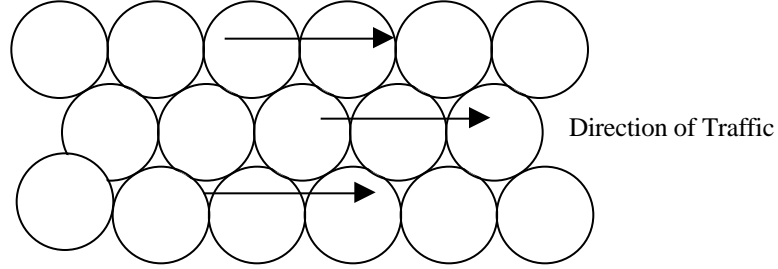


Figure 20. The optimal packing of PAZ circular regions allowing one flow direction.

A slightly less constrained limit occurs when opposite flows of traffic fly side by side. Figure 21 illustrates the geometry of opposite flows of traffic. In this case, the maximum number of aircraft N_{\max} that can fit within a reference area A_{ref} is defined by:

$$\frac{N_{\max} \pi R^2}{A_{\text{ref}}} = \frac{\pi}{4} = 0.785 \quad (4.19)$$

The upper limit on dynamic density would then be:

$$\delta_{\max} = \frac{N_{\max}}{A_{\text{ref}}} = \frac{0.785}{\pi R^2} \quad (4.20)$$

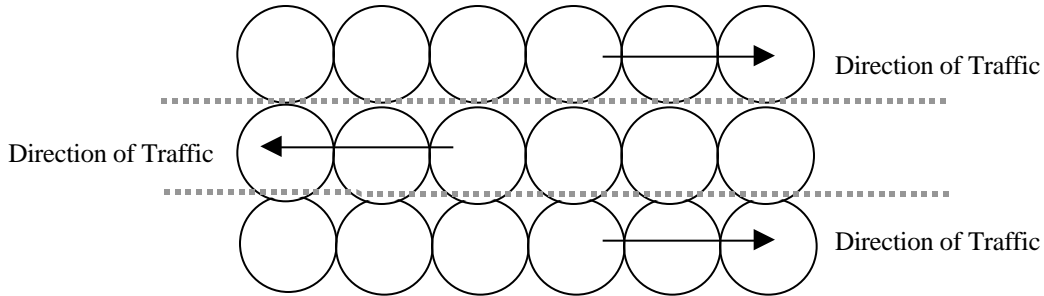


Figure 21. The optimal packing of PAZ circular regions allowing two flow directions.

The Nearest Neighbor (NN) graph or other an algorithmic solution approach can be used to define the distance to the nearest neighbor of aircraft i , the solution to a minimization problem over the distances d_{ij} between aircraft i and aircraft j . A formal method of maintaining the nearest neighbor information is using a Delaunay Triangulation [PS85, OBS92] of the set of N points, where each point corresponds to the location of one of the N aircraft. Delaunay Triangulations are spatial data structures from computational geometry that allow for rapid identification of nearest neighbors. For all aircraft in the system, aircraft are represented as points in the triangulation, and edges identify nearest neighbors, as shown in Figure 22.

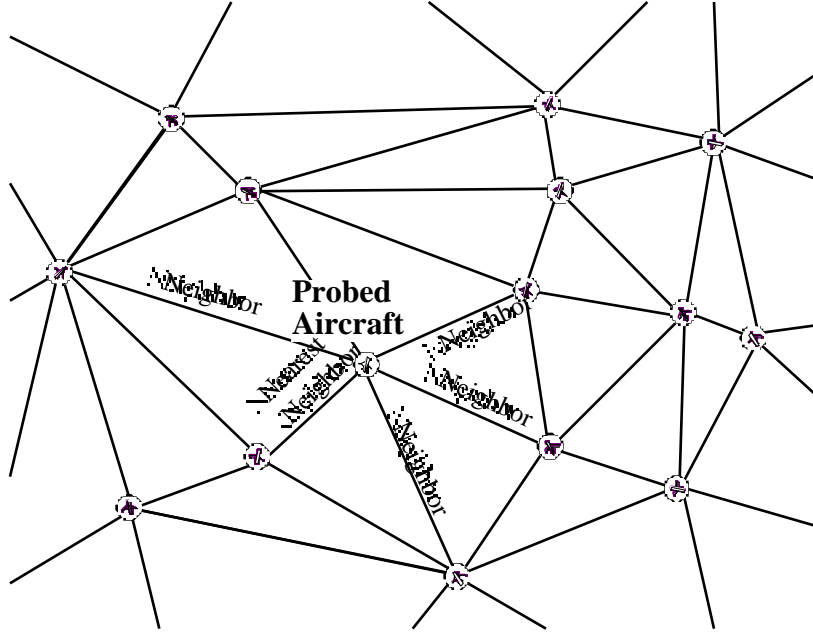


Figure 22. A Delaunay Triangulation of N aircraft.

A Delaunay Triangulation is defined as follows. A triangulation for points in a two-dimensional geometric plane is a straight line graph partitioning of a set of N points such that no two edges intersect at any point other than the N data points. The Delaunay Triangulation has the additional property that the circumcircle of any triangle in the triangulation contains no point (in the set of N points) in its interior. Given four points A located at (x_A, y_A) , B located at (x_B, y_B) , C located at (x_C, y_C) , and D located at (x_D, y_D) , the test to identify if point D is within the circumcircle defined by points A , B , and C is determined by the criterion [GS85]:

$$(4.21) \quad \begin{vmatrix} x_A & y_A & x_A^2 + y_A^2 & 1 \\ x_B & y_B & x_B^2 + y_B^2 & 1 \\ x_C & y_C & x_C^2 + y_C^2 & 1 \\ x_D & y_D & x_D^2 + y_D^2 & 1 \end{vmatrix} > 0.$$

This equation must hold for all triangles defined by the points A , B , and C in the Delaunay Triangulation. Figure 23 illustrates the Delaunay Triangulation for a set of aircraft composed of two streams of traffic. In addition to the aircraft, four sector corners are used as stationary points in the Delaunay Triangulation to identify the proximity of the aircraft to the sector boundaries. As the aircraft progress forward, the Delaunay Triangulation dynamically changes. At any given instant, though, the nearest neighbors of any aircraft can be identified by the edges in the Delaunay Triangulation.

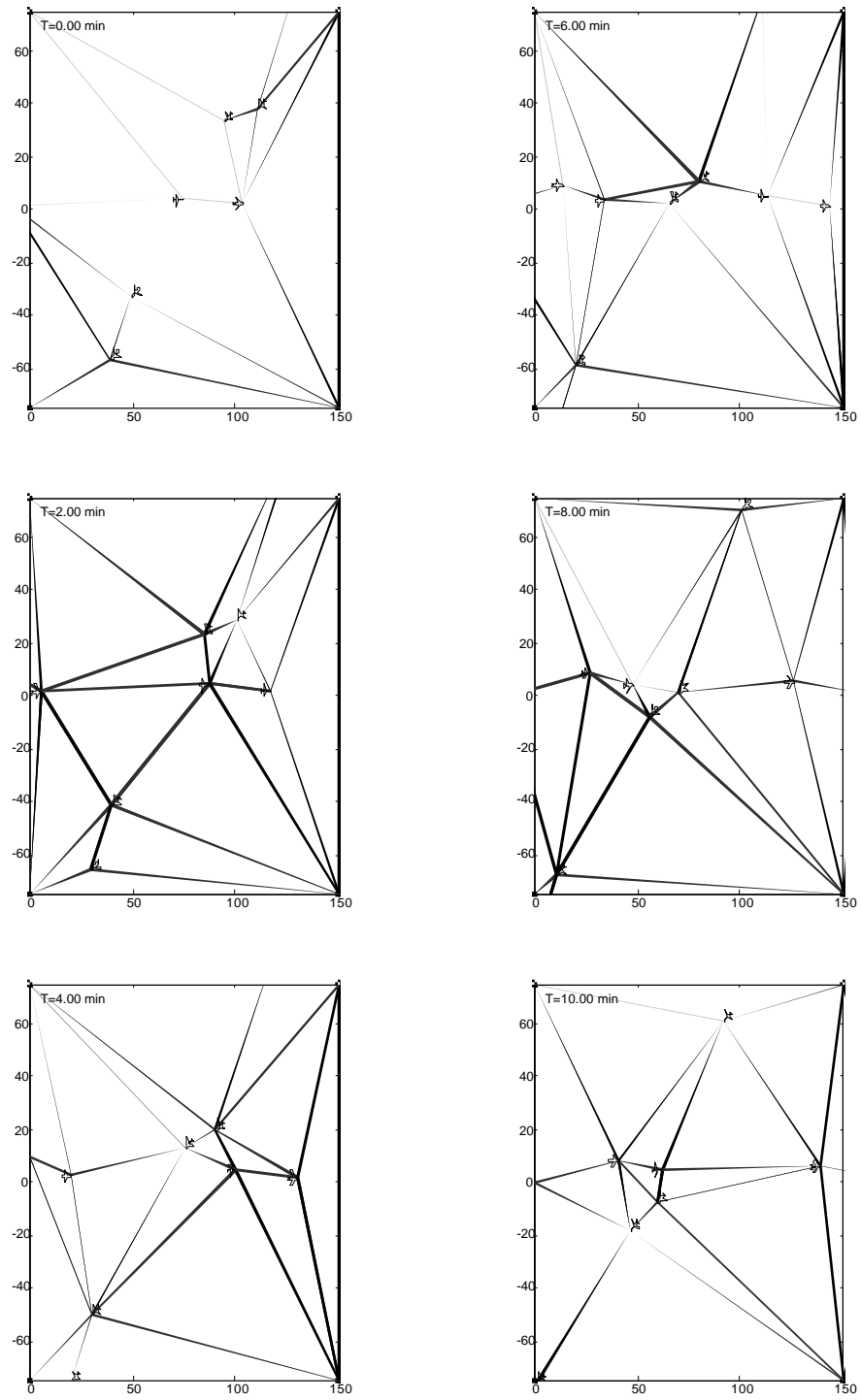


Figure 23. Each window depicts a snapshot of the Delaunay Triangulation at 2 minute intervals.

4.2 System Stability

System stability in our investigation is related to the system variables that give rise to the potential of a “domino effect”, where the resolution of a conflict between two aircraft propagates into causing a subsequent conflict with three or more aircraft before the conflict can be resolved. To start the modeling for stability, consider the following rationale for characterizing the domino effect using two overlapping sets of aircraft.

S_1 : The set of all aircraft that have a conflict alert when no conflict resolution algorithms are on, and

S_2 : The set of all aircraft that have a conflict alert when conflict resolution algorithms are on,

and the overlapping regions:

R_1 : The aircraft predicted to have a conflict alert without conflict resolution on, but did not have a conflict alert when conflict resolution was on;

R_2 : The aircraft predicted to have a conflict alert without conflict resolution on, and did have a conflict alert when conflict resolution was on; and

R_3 : The aircraft not predicted to have a conflict alert without conflict resolution on, but did have a conflict alert when conflict resolution was on.

For system stability, we primarily measured the domino effect by the set R_3 . Figure 24 illustrates how the domino effect term R_3 is represented from two overlapping sets:

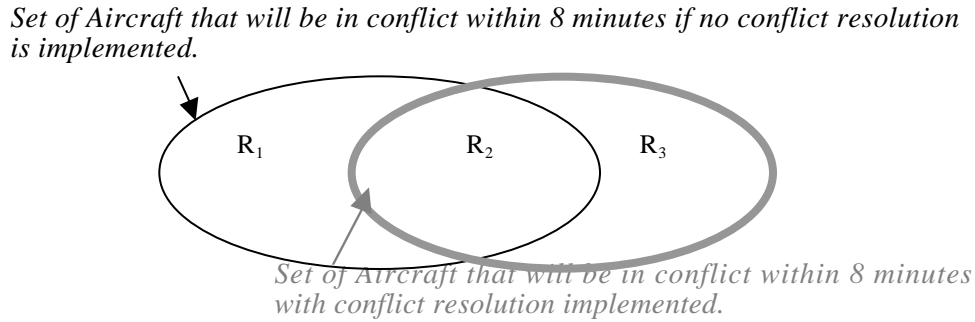


Figure 24. Three distinct regions of two overlapping sets describes the effects of conflict resolution and the “domino effect” (Region R_3).

Several definitions for the domino effect, E_d , are next considered. The most obvious definition for domino effect would be R_3 itself. However, the problem with R_3 is that the number would be meaningless without some reference to the number of aircraft in the system. Therefore, R_3 was normalized by n , the number of aircraft which ran in the simulation within a specified unit of time. The term n should not be confused with the aircraft density of the simulation. Such a definition of the domino effect could be represented as:

$$E_d = \frac{R_3}{n}. \quad (4.22)$$

However, the use of R_3 alone for a stability measure does not account for the possibility that aircraft that originally would have conflict alerts when no conflict resolution is implemented may not actually have a conflict alert because of previous maneuvers performed during conflict resolutions (by the ownship or by other aircraft). This system stabilizing effect is characterized by R_1 . To compensate for the stabilizing effect, the domino effect can be redefined:

$$E_d = \frac{R_3 - R_1}{n}. \quad (4.23)$$

Yet another concern is that n may not be the best normalizing value. The domino effect is ideally a comparison of the additional number of conflicts alerts compared to the number of nominal conflict alerts (with no conflict resolution on) rather than the total number of aircraft in the simulation. The term S_1 best represents the normalization:

$$E_d = \frac{R_3 - R_1}{S_1}. \quad (4.24)$$

The end result is that the domino effect characterizes the additional number of aircraft which have to deviate because of conflict resolution normalized with the initial number of aircraft that had conflict alerts. This expression can be mathematically manipulated into a form independent of the notation of the regions R_1 , R_2 , and R_3 , and solely in terms of the sets S_1 and S_2 :

$$\frac{R_3 - R_1}{S_1} = \frac{S_2}{S_1} - 1. \quad (4.25)$$

Indeed, it is the ratio of the two sets S_1 and S_2 that characterize the stability of the system. The value of 1 (or -1) simply acts as a reference. Thus, we next consider only the terms S_1 and S_2 in the system stability measure.

Through our experiments, we noticed that using R_3 as a characterization of the domino effect does not reveal any significant system stability information for high densities. High density airspace usually results in so many conflicts that the number of additional undisturbed aircraft for which the domino effect can propagate is small. In high density cases, R_3 usually goes down towards zero yet S_1 increases. This phenomena is also present in the metric in Equation (4.24) indicating a reduction of the domino effect during system conflict saturation. For this reason a new definition for the two sets S_1 and S_2 was considered:

S_1 : The total number of conflict alerts that occur for the set of aircraft that experience conflict alerts when no conflict resolution algorithms are implemented.

S_2 : The total number of conflict alerts that occur for the set of aircraft that experience conflict alerts when no conflict resolution algorithms are implemented.

With the new definition of S_1 and S_2 the total number of conflicts that occur are considered instead of just the number of aircraft that experience conflicts. Therefore, the domino effect is characterized by the additional number of conflict alerts rather than the additional number of aircraft involved. One problem with this technique is that it precludes dividing S_1 and S_2 into the three original overlapping regions R_1 , R_2 , and R_3 because conflict alerts depend on complete history of flight. Equation (4.24) can not be used directly. But as mentioned, equation (4.25) provides the stability ratio of interest in terms of S_1 and S_2 . So as to characterize a decreasing stability situation with a metric that decreases as well, we invert the relationship leaving us with the final stability metric as shown in Equation (4.26).

$$\text{System Stability} = \frac{S_1}{S_2}. \quad (4.26)$$

In the experiments of Chapter 6, Equation (4.26) is used as the system stability measure.

5.0 IMPLEMENTATION AND DEMONSTRATION

This chapter presents the results of our modeling and simulation effort for a decentralized control system. The DAG TS concept is modeled in a simulation environment that includes aircraft and airspace modeling. Additionally, a communication mechanism is modeled.

The simulated aircraft are piloted with an internal guidance, navigation, and control package. The control algorithms allow for realistic piloting of climbs, descents, turns, and terminal flight phases. The guidance package allows the aircraft to fly to fixes and follow user preferred routes. Speed and altitude constraints can also be established at fixes along a route. The real-time capability of the simulation allows the operator to change routes during the operation of the simulation as well as to manually vector aircraft through maneuvers. The simulation allows aircraft to follow flight plans, and for aircraft to receive the state and next one or two waypoints of another aircraft in order to simulate the ADS-B message passing possibility of Free Flight.

The simulation has the following features:

- Realistic Speed and Altitude changes
- Realistic Turn Dynamics
- Fix Capture Capability
- Route Capture and Route Following
- Capability of meeting Speed and Altitude Restrictions at Fixes
- Random Scenario Generation

The aircraft simulation is based on a 4 degree of freedom model that captures the Phugoid mode and Roll mode dynamics for aircraft. The aerodynamic modeling for the aircraft is based on drag polars which are representative of the specific aircraft being modeled. The engines are modeled using polynomial curve fits that calculate the engine thrust and fuel burn based on the aircraft's speed, altitude, and the current atmospheric conditions. While running the simulation, aircraft states can be monitored. Available state variables include: true airspeed, indicated airspeed, Mach, altitude, vertical speed, engine thrust, lift coefficient, heading, ground track, turn rate, and weight. Since much of this functionality is not needed for the purely horizontal experiments performed, a detailed discussion of the longitudinal capabilities is not required. Readers interested in the explicit functionality of the system are referred to [P99].

5.1 Lateral Directional Dynamics

The lateral directional models the aircraft's turn dynamics. The four topics for discussion are:

1. The bank angle capture algorithm
2. The heading capture algorithm
3. Using the Bank Angle Capture and Heading Capture Algorithms to execute a turn
4. Deciding which way to turn

5.1.1 The Bank Angle Capture Algorithm

The bank angle capture algorithm is the major kernel of the lateral directional control law. Consider the governing lateral directional equations of motion shown in Equations (5.1) through (5.3). The first two equations characterize the aircraft's response in roll to the aileron deflection. Equation (5.3) characterizes the aircraft's turn rate with respect to a given bank (or roll) angle.

$$\dot{p} = L_p p + L_{\delta_a} \delta_a \quad (5.1)$$

$$\dot{\phi} = p \quad (5.2)$$

$$\dot{\psi} = \frac{LS_\phi}{mV_a C_{\gamma_a}} \quad (5.3)$$

The only input to the system is the aileron deflection and the state variables of immediate interest are the roll rate p and the bank angle, ϕ . The equations of motion can be written in state space as shown in Equation (5.4).

$$\begin{bmatrix} \dot{p} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{L\delta_a}{mV_a C_{\gamma_a}} & 0 \end{bmatrix} \begin{bmatrix} p \\ \phi \end{bmatrix} + \begin{bmatrix} \frac{L\delta_a}{mV_a C_{\gamma_a}} \\ 0 \end{bmatrix} \delta_a \quad (5.4)$$

For feedback control we choose to feed back both p and ϕ so that we can control both the frequency and the damping of the roll mode. The closed loop block diagram is shown in Figure 25.

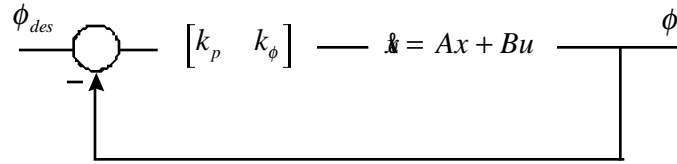


Figure 25. Block diagram for the rolling dynamics.

The closed loop state space equations are:

$$\begin{bmatrix} \dot{p} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -L\delta_a k_p & -L\delta_a k_\phi \\ 1 & 0 \end{bmatrix} \begin{bmatrix} p \\ \phi \end{bmatrix} + \begin{bmatrix} L\delta_a k_p \\ 0 \end{bmatrix} \phi_{des} \quad (5.5)$$

5.1.2 The Heading Capture Algorithm

The heading capture algorithm is designed to capture a specified heading. To capture a given heading, we feed back the desired heading to the bank angle using the control law as shown in Equation (5.6).

$$\phi_d = k_\psi \psi_d - \psi \quad (5.6)$$

To predict the effect of this feedback control law, we must first add the heading equation to our state space model. Consider the linearized version of the turn rate equation which finds its way into our state matrix.

$$\frac{d\psi}{d\phi} = \frac{d}{d\phi} \left[\frac{LS_\phi}{mV_a C_{\gamma_a}} \right] \Delta\phi \quad (5.7)$$

$$\frac{d\psi}{dp} = 0 \quad (5.8)$$

If we assign our reference condition for the linearization to be $\psi = 0.0$, $\Delta\phi = \phi$. Furthermore, if we note that for the bulk of the flight the lift equals the weight and the flight path angle is near zero, we can simplify Equation (5.7) to Equation (5.9).

$$\frac{d\psi}{d\phi} \equiv \frac{g}{V_a} \phi \quad (5.9)$$

Arranging the system of equations in state space we have Equation (5.10).

$$\begin{bmatrix} L_{\delta_a} k_p & -L_{\delta_a} k_\phi & 0 \\ 1 & 0 & 0 \\ 0 & \frac{g}{V_a} & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \phi \\ \psi \end{bmatrix} \quad (5.10)$$

When we close a proportional loop around the system with k_ψ as our feedback gain, as shown in Figure 26, the new closed loop system is described by Equation (5.11). An integrating relationship between the heading and the roll angle occurs so zero steady state error is achieved without using integral control.

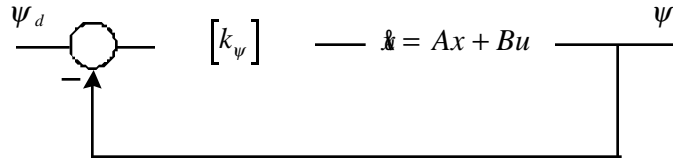


Figure 26. Block diagram for heading feedback.

$$\begin{bmatrix} L_{\delta_a} k_p & -L_{\delta_a} k_\phi & -L_{\delta_a} k_\phi k_\psi \\ 1 & 0 & 0 \\ 0 & \frac{g}{V_a} & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \phi \\ \psi \end{bmatrix} \quad (5.11)$$

Further verifying that integral control is unnecessary, we see that the transfer function which characterizes the relationship between ψ and ψ_d , Equation (5.12), has a DC gain of 1.

$$\frac{\psi}{\psi_d} = \frac{\frac{g}{V_a} L_{\delta_a} k_\phi k_\psi}{s^3 + d_p + L_{\delta_a} k_p s^2 + L_{\delta_a} k_\phi s + \frac{g}{V_a} L_{\delta_a} k_\phi k_\psi} \quad (5.12)$$

5.1.3 Using the Bank Angle Capture and Heading Capture Algorithms to Execute a Turn

When turning, the heading capture algorithm can not be used for large heading errors. Since the heading capture algorithm will command a bank angle proportional to the heading error, if the heading error is large, the control law will command an unreasonably large bank angle such as 180 degrees. This bank angle would correspond to an inverted aircraft and certainly does not make the aircraft turn any faster. Therefore, the heading capture algorithm is used only when the heading error is less than 15 degrees. For errors greater than 15 degrees, the bank angle control law is used to command a constant turn rate in the direction of minimizing the heading error. Nominally, a bank angle of 30 degrees is used.

$$\begin{aligned} \text{if } \psi_d > \psi & \quad \text{if } \psi_d < \psi \\ e_{\text{right_turn}} &= \psi_d - \psi & e_{\text{right_turn}} &= \psi_d - \psi \\ e_{\text{left_turn}} &= \psi_d - \psi & e_{\text{left_turn}} &= \psi_d - \psi \end{aligned}$$

Next, the absolute value of $e_{\text{right_turn}}$ and $e_{\text{left_turn}}$ are compared to determine which is smaller. The actual heading error, e_s , is set equal to the smaller of these two errors. Turning errors to the left are defined negative and turning errors to the right are positive, as shown in Figure 27. This corresponds

nicely to the bank angle convention where banks to the right are considered positive and banks to the left are negative. Therefore, there is no need to adjust the previously developed control laws to make sure that the aircraft turns in the desired direction when commanded.

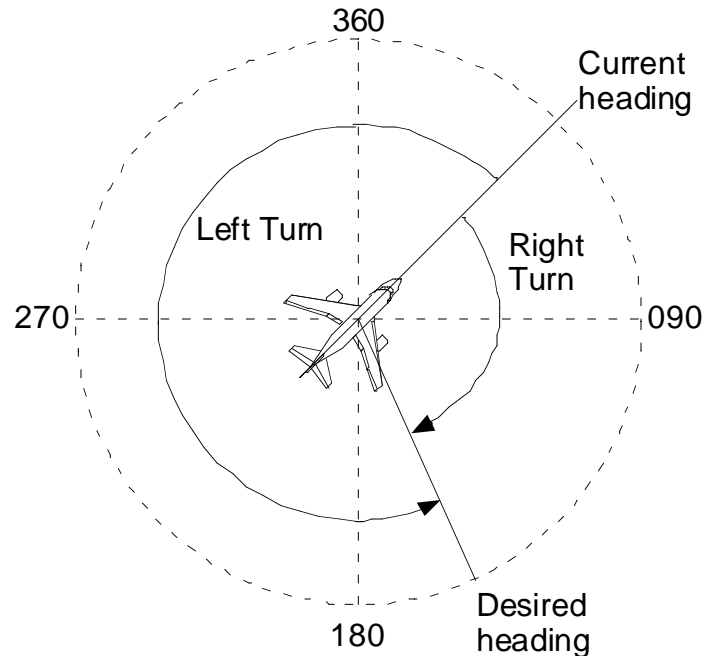


Figure 27. An illustration of the dilemma of whether to make a right of left turn to a heading.

Finally, note that there are times when the circumstance demands the aircraft turn in the direction opposite to what is actually the shortest turn. Therefore, either navigator must be able to override the turning logic and specify a left or right turn in the simulation. This is the topic for the next section.

5.2 Lateral Guidance System

The lateral guidance system steers the aircraft to follow routes or other commands within the horizontal plane. There are four basic maneuvers:

- Ground track guidance
- Fix capture guidance
- Route following
- Route capture

The ground track guidance algorithm steers the aircraft along a specified ground track from the flight plan. In the presence of wind, the algorithm must determine a wind correction angle to the aircraft heading to maintain the ground track. The fix capture algorithm flies the aircraft to a fix. Route following steers the aircraft along a specified route. Finally, the route capture algorithms are discussed. The route capture algorithms steer the aircraft towards a route and then capture the route. Several different ways to capture a route will be discussed.

5.2.1 Ground Track Guidance

The ground track angle is the angle between the aircraft's ground track and true North. Under a zero crosswind condition, the ground track angle is the same as the aircraft's heading. However, when the wind is non-zero, the ground track angle will be different than the aircraft heading as illustrated in Figure 28. Therefore, to properly fly to a fix or capture a route, the aircraft will need to turn to a given ground track angle rather than a specific heading. The lateral control system is designed only to turn to a desired heading, so the lateral guidance must bias its heading commands to the lateral control system with a correction factor to account for winds. To accommodate this requirement, the lateral guidance measures the difference between the heading and the ground track angle, $\Delta\psi$.

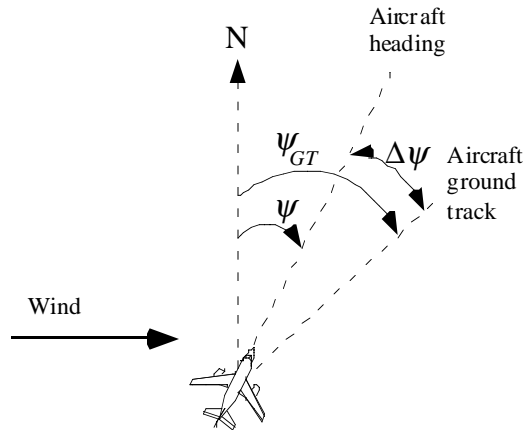


Figure 28. Illustration of the difference between ground track and heading.

The ground track guidance system guides the aircraft along a specified ground track instead of following a specified heading. This algorithm consists of a wind correction algorithm which allows the aircraft to follow a specified ground track in the presence of wind. The algorithm makes use of the following nomenclature:

- ψ : the aircraft's heading in degrees.
- ψ_{GT} : the aircraft's ground track in degrees.
- $\Delta\psi$: the difference between the aircraft's ground track and heading.
- ψ_d : the desired heading.
- ψ_{GT_d} : the desired ground track.

The difference between the aircraft's ground track and heading is calculated using Equation (5.15).

$$\Delta\psi = \psi_{GT} - \psi \quad (5.13)$$

The aircraft's ground track and heading are available from the aircraft dynamics. This correction factor, $\Delta\psi$, is then used to adjust the desired ground track so that the aircraft will track properly. The result, calculated using Equation (5.15), is the desired heading.

$$\psi_d = \psi_{GT_d} - \Delta\psi \quad (5.14)$$

Before the desired heading is used, it must be checked to make sure that it is within the proper boundaries as shown in Figure 29. Once the heading has been checked, it can be sent to the control logic as a new heading command.

5.2.2 Fix Capture Guidance

To fly to a fix, the range and azimuth to the fix are used. Algorithms which perform these operations are discussed later. Once the azimuth of the fix is known, the turn-to-heading logic is used to turn the aircraft to that azimuth. This control strategy is effective as long as the aircraft is sufficiently far away from the fix so that the azimuth angle is not changing quickly as seen in Figure 30. Keep in mind that as the aircraft moves, the azimuth angle is constantly changing except when flying directly to the fix.

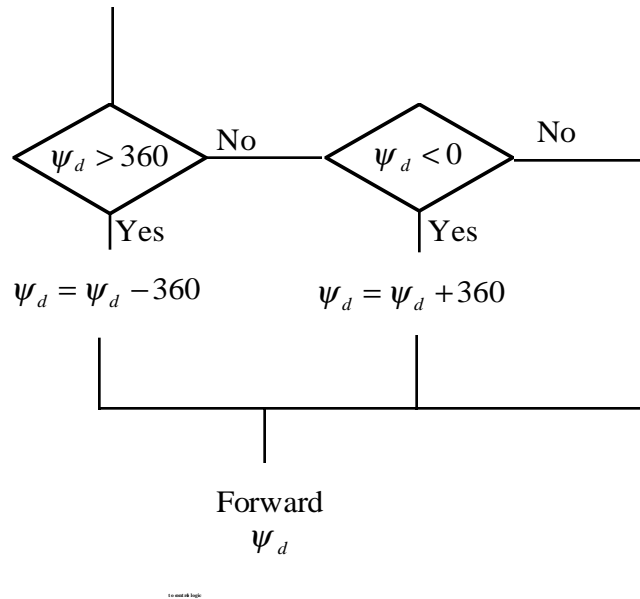


Figure 29. Logic for insuring desired heading is within proper boundaries.

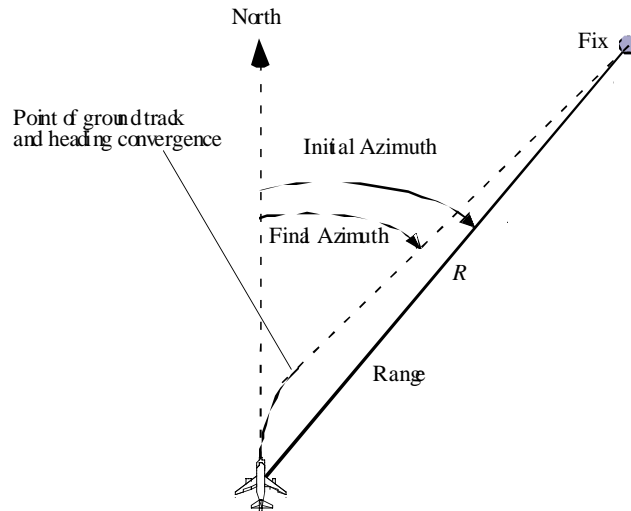


Figure 30. An aircraft turning to a fix.

5.2.3 Route Following

When flying a particular segment, the route following algorithm commands the ground track of the aircraft based on the lateral distance that the aircraft is away from the segment, the capture segment's bearing, and the aircraft's radius of turn. The scenario is illustrated in Figure 31. The intercept angle for the given segment is a function of how far the aircraft is laterally from the segment.

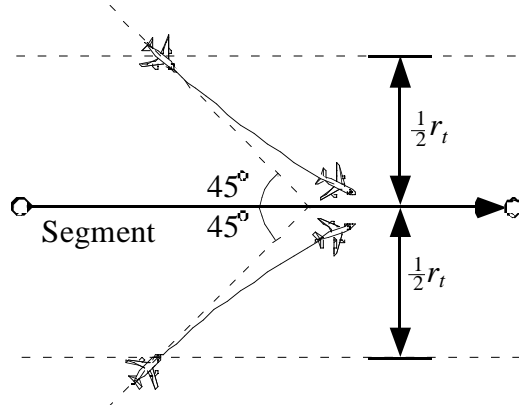


Figure 31. Illustration of the aircraft in route following mode.

The intercept reaches a maximum of 45 degrees when the aircraft is one-half a turn radii away from the segment. The intercept angle is bounded at 45 degrees. Equations (5.15) and (5.16) determine the aircraft's desired ground track. First, $\Delta\psi$ is calculated using Equation (5.15). If the result has a magnitude greater than 45 degrees, the answer is bounded at 45 degrees using Equation (5.16). The ratio $\frac{\delta}{|r_t|}$ is used to preserve the sign of the original value. Note that the lateral distance term, δ , maintains a sign convention of positive values on the right side of a segment and a negative value on the left side of the segment. This solution is adapted from the original System Segment Specification [TGF93].

$$\Delta\psi = 90 \frac{\delta}{r_t} + \delta\psi_{fe}, \quad |\Delta\psi| < 45^\circ \quad (5.15)$$

$$\Delta\psi = 45 \frac{\delta}{|r_t|}, \quad |\Delta\psi| \geq 45^\circ \quad (5.16)$$

$$\psi_{GT_d} = \psi_r - \Delta\psi \quad (5.17)$$

The terms are defined as follows:

- δ : The aircraft's lateral perpendicular distance from the capture segment (nm)
- ψ_r : The capture segment's bearing. (degrees)
- r_t : The aircraft's turn radius. (nm)
- ψ_{GT_d} : The aircraft's desired ground track (degrees)
- $\delta\psi_{fe}$: The heading bias from flight technical error (degrees)

5.2.4 Capturing a Route

A route in the aircraft simulation consists of a list of fixes. Segments in the simulation are defined by adjacent fixes along a route. There are three ways to used to capture a route:

1. Automatic route capture
2. Vectored route capture, and
3. Initial fix route capture.

When using automatic route capture, the aircraft guidance performs all of the necessary operations to determine which segment should be captured first and then steer the aircraft toward the segment. Finally, the capture algorithm merges onto the route. The vectored route capture algorithm requires manual guidance of the aircraft to the route; however, once the aircraft is sufficiently close to the

route, the guidance algorithm merges the aircraft with the route. The last route capture algorithm is the initial fix route capture. This algorithm flies the aircraft to the initial fix first and then captures the route.

5.2.5 Determining When to Merge Onto a Route

When an aircraft approaches a segment on a route, it must gauge when it should start to turn to merge cleanly onto the route. Generally, the distance that is required is a function of the aircraft's speed and the intercept angle that the aircraft has with the segment. It is a very similar calculation to that which is used for segment transition. Figure 32 illustrates the geometry of an aircraft merging onto a segment

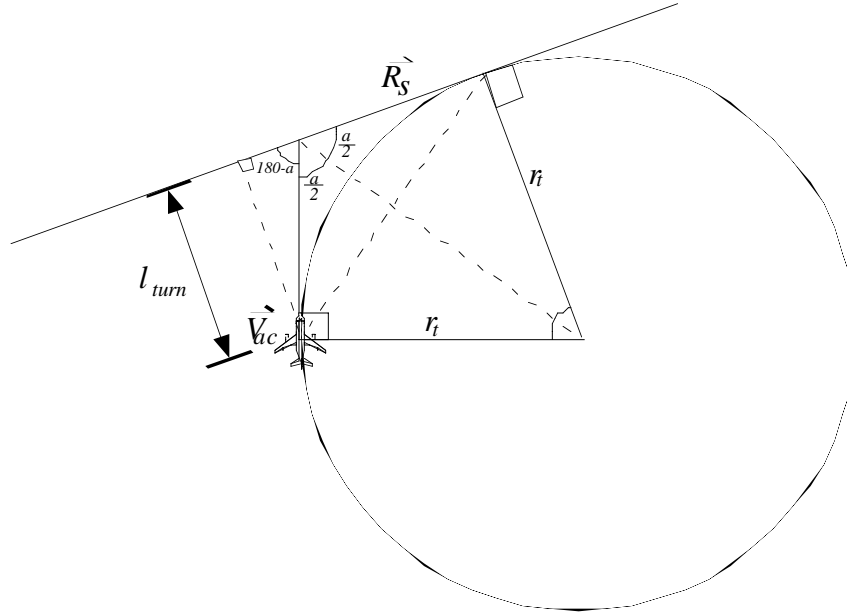


Figure 32. Illustration of geometry associated with an aircraft merging onto a segment when aircraft is heading in the direction of the segment.

The algorithm requires the aircraft's true airspeed and heading and a vector describing the segment, where V_a : is the aircraft's true airspeed (ft/sec), ψ : is the aircraft's heading (deg), and R_s : is a vector describing a segment.

First, a vector V_{ac} representing the aircraft's velocity is created from the aircraft's speed and heading. Using the definition of the dot product, the angle between the vectors is calculated using Equation (5.18).

$$\cos^{-1} \left(\frac{V_{ac} \cdot R_s}{|V_{ac}| |R_s|} \right) = \frac{a}{2} \quad (5.18)$$

Evident from the geometry in Figure 32, the problem is similar to the segment transition problem. The distance at which the aircraft should turn, l_{turn} , is the projection of l_{offset} onto a line normal to the segment. Therefore it can be calculated using Equation(5.19), where r_t it the turn radius of the aircraft in nm.

$$l_{turn} = 1.3r_t \tan \left(\frac{a}{2} \right) \sin(180 - a) \quad (5.19)$$

Using the trigonometry identity $\sin a = \sin(180 - a)$, Equation (5.20) can be simplified to:

$$l_{turn} = 1.3r_t \tan \frac{a}{2} \sin a \quad (5.20)$$

When the aircraft is tending to head in the direction opposite the direction of the segment, more distance is needed to turn because the aircraft must completely change the direction of flight to fly along the segment. This case is illustrated in Figure 33. However, Equation (5.20) is still valid as can be verified from inspection of the geometry in Figure 33.

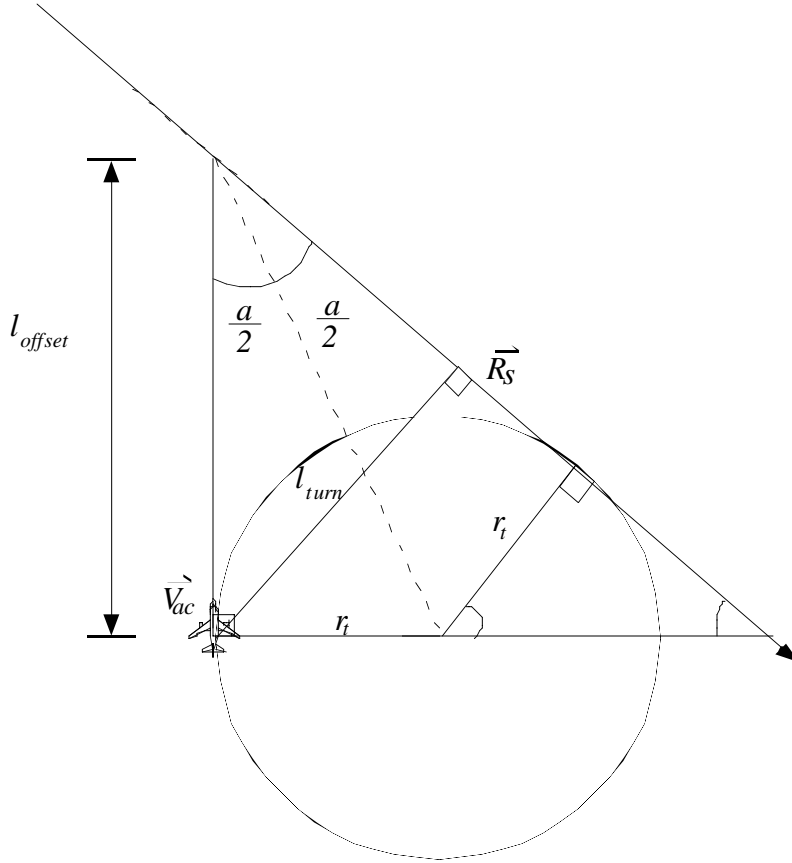


Figure 33. An aircraft merging onto a segment which is pointed in a direction opposite of the aircraft's current velocity.

5.3 Communications

A simple model for communications is used for air-to-air communications and air-to-ground / ground-to-air communications. No data dropouts or transport anomalies are modeled. Air-to-air communications are modeled by communications being completed to all aircraft within a given range of a transmitting aircraft. Air-to-ground and ground-to-air communications are assumed to have no range limit.

5.4 Scenario Generation

The simulation has the ability to generate random scenarios which allow for Monte-Carlo testing of decentralized control algorithms. The ability to generate random scenarios allows the user to specify different levels of congestion and dynamic density without having to manually build each scenario.

The scenario generator starts with an initial 'ground zero' reference point and draws two circles of 100 nmi and 120 nmi radii respectively around the reference point. Then fix locations are determined along the edges of the defined airspace and route segments are drawn in between pairs of fixes. An aircraft flies from a fix on the outer circle to a fix on the inner circle. The reason for the outer circle is to prevent newly initiated aircraft from being in immediate conflict with aircraft currently in the simulation. Figure 34 illustrates a randomly generated scenario.

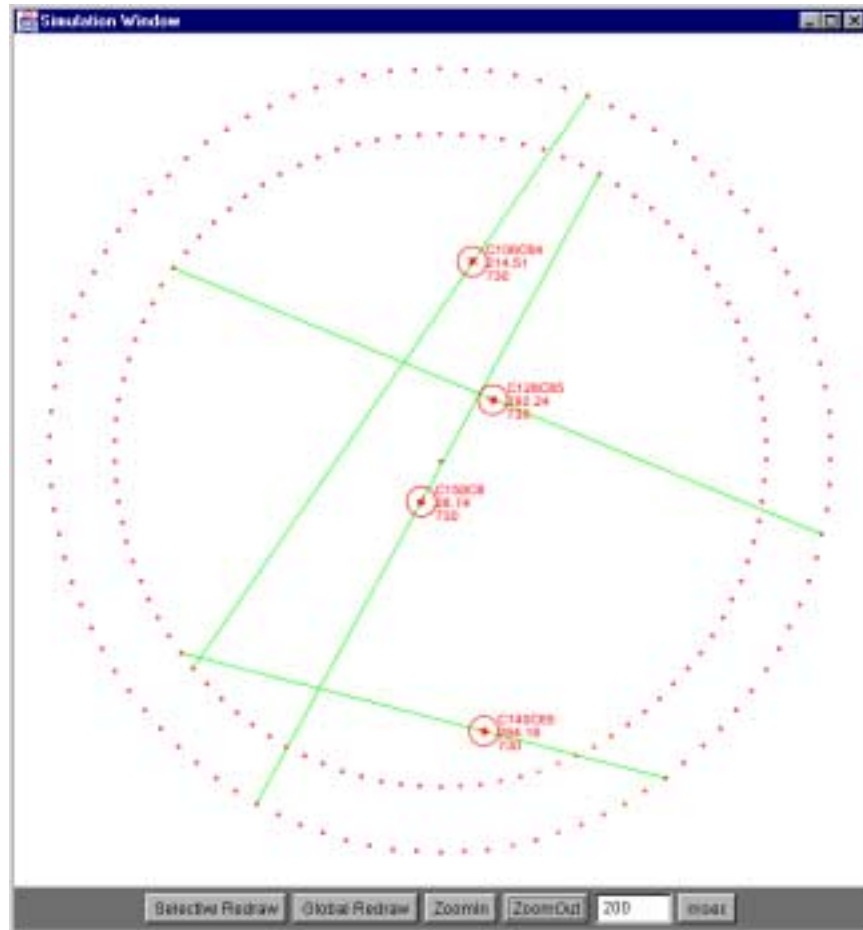


Figure 34. Illustration of a random scenario and initial conflicts identified.

6.0 SIMULATION RESULTS

In this chapter, we present Monte Carlo simulation results based on the modeling and simulation derivations of Chapters 4 and 5. Aircraft simulation data were analyzed for instantaneous properties as well as time cumulative properties. Monte Carlo simulations were run to collect a large body of data. At the end of this chapter, plots of stability and performance summarize the most general results from these data.

Instantaneous properties were studied using four main aircraft density levels. These density levels are 20, 40, 60, and 80 aircraft scenarios within the 100 nmi radii reference region. These aircraft numbers translate into simple density numbers of:

- $0.00064 \frac{\text{aircraft}}{\text{nmi}^2}$ for the 20 aircraft scenario,
- $0.0013 \frac{\text{aircraft}}{\text{nmi}^2}$ for the 40 aircraft scenario,
- $0.0019 \frac{\text{aircraft}}{\text{nmi}^2}$ for the 60 aircraft scenario, and
- $0.0025 \frac{\text{aircraft}}{\text{nmi}^2}$ for the 80 aircraft scenario.

During these scenarios, the following information was recorded every time step:

- Predicted Conflicts
- Actual Conflicts
- Simple Density $n_{ac} A_{PAZ} / r_{ref}$
- Nearest Neighbor (represented as $r_{PAZ} / r_{nearest}$ An increasing number suggests a more critical situation)
- Point of Closest Approach with nearest neighbor
(represented as $K_{PAZ} / PCA_{nearest}$ An increasing number suggests a more critical situation)

Predicted and actual conflict data were collected in both conflict resolution and no-resolution scenarios. Resolution without a look-ahead feature was compared to resolution with look-ahead. Furthermore, predicted conflicts were analyzed to see how many were exclusive to the no-resolution and resolution scenarios. The purpose of this check was to see if any domino effect or other instabilities (e.g., any evidence of a chaotic effect) could be detected by observing instantaneous data.

6.1 Low Density

The low density case is shown in Figure 35 through Figure 43.

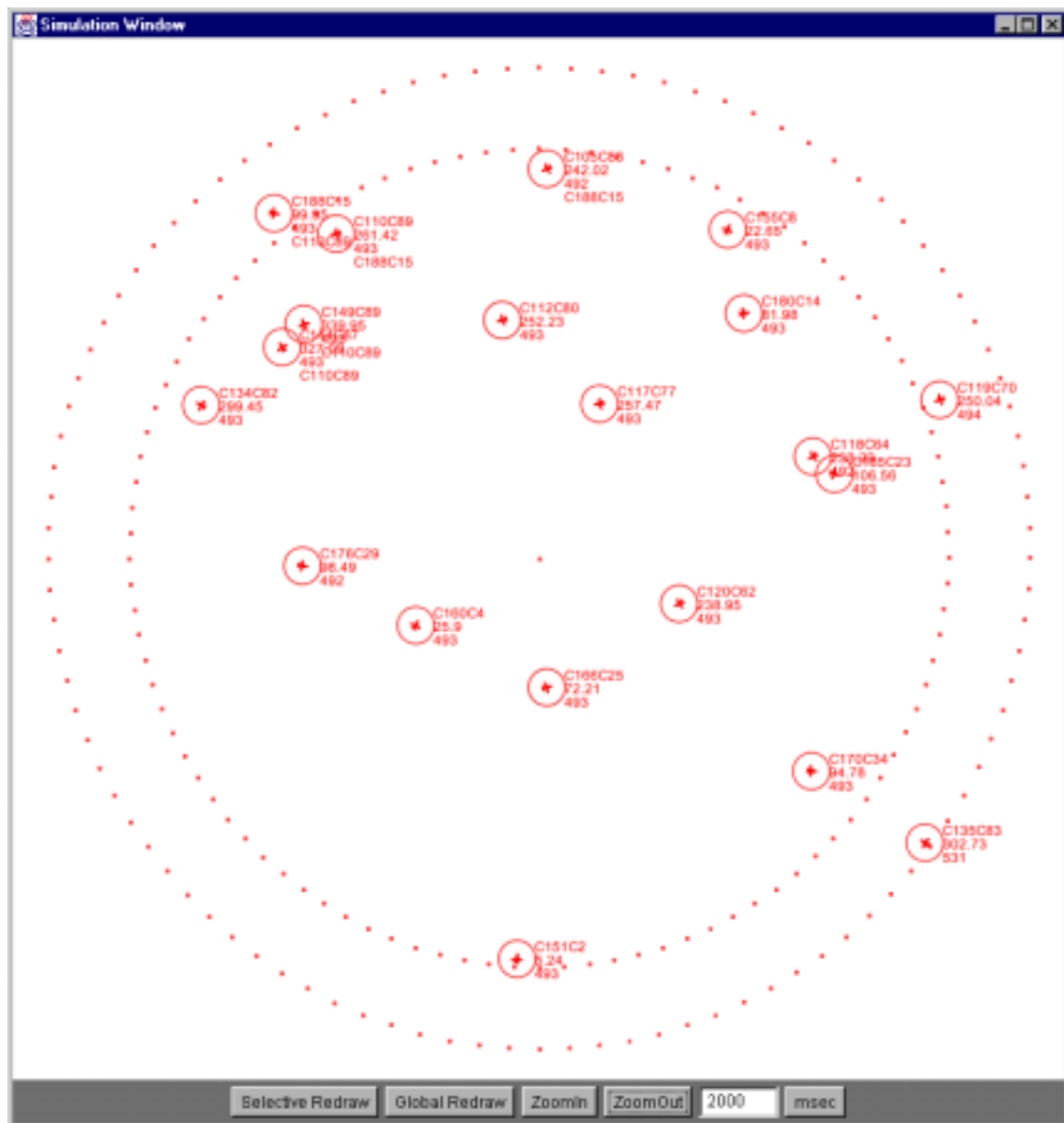


Figure 35. Simulation screenshot at low density.

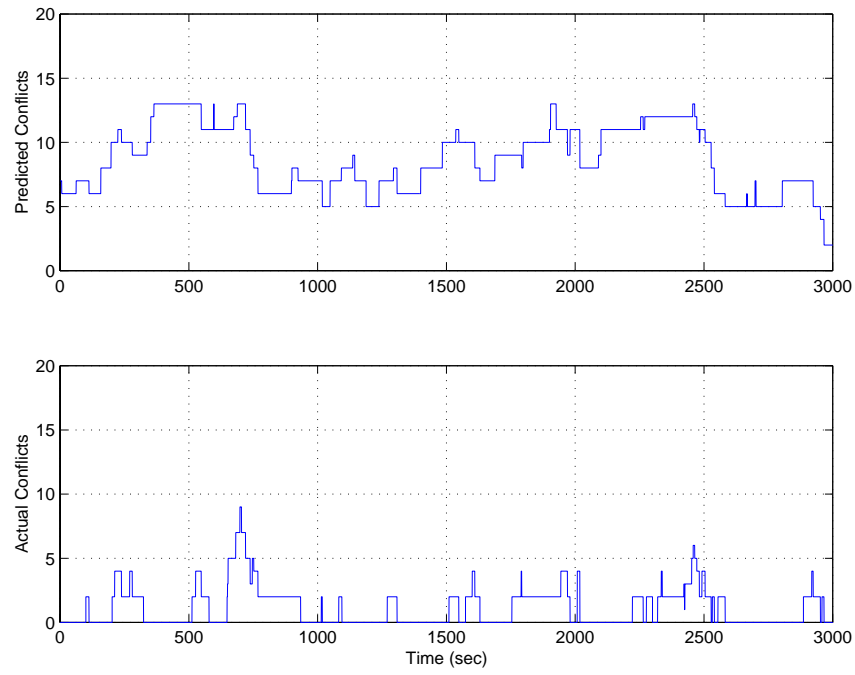


Figure 36. Predicted and actual conflicts for the low density case with no conflict resolution.

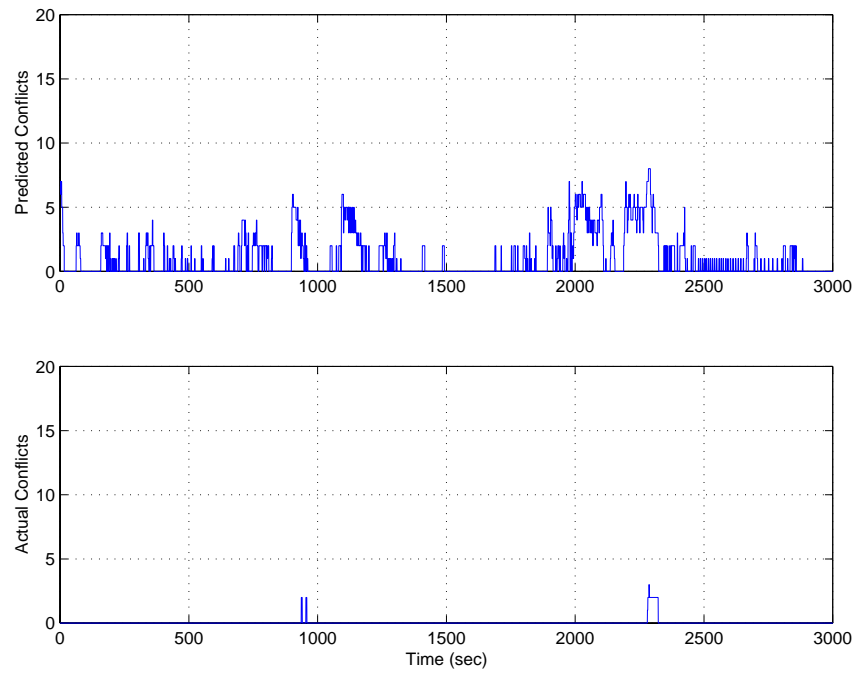


Figure 37. Predicted and actual conflicts for the low density case with decentralized conflict resolution.

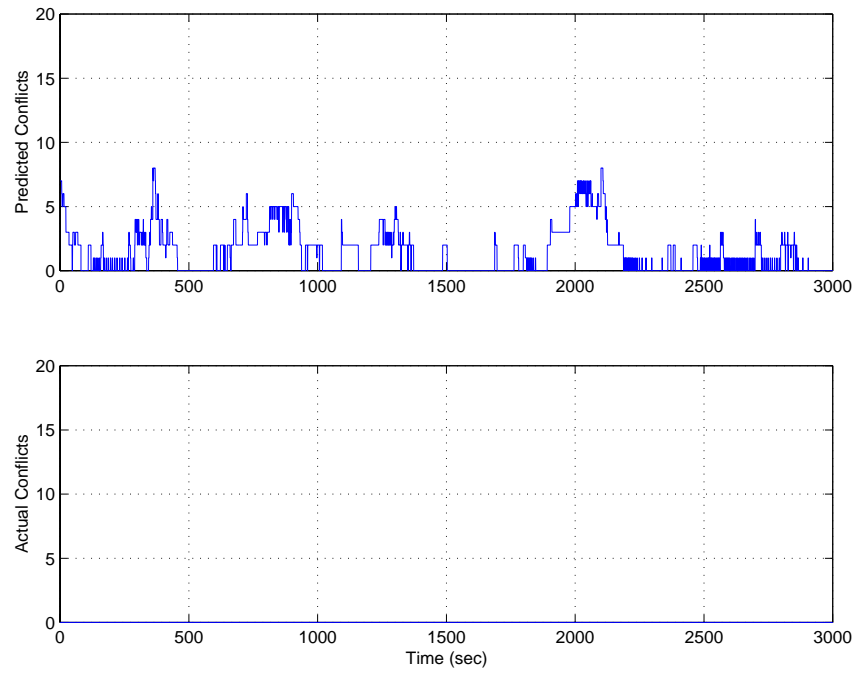


Figure 38. Predicted and actual conflicts for the low density case with decentralized conflict resolution with look ahead.

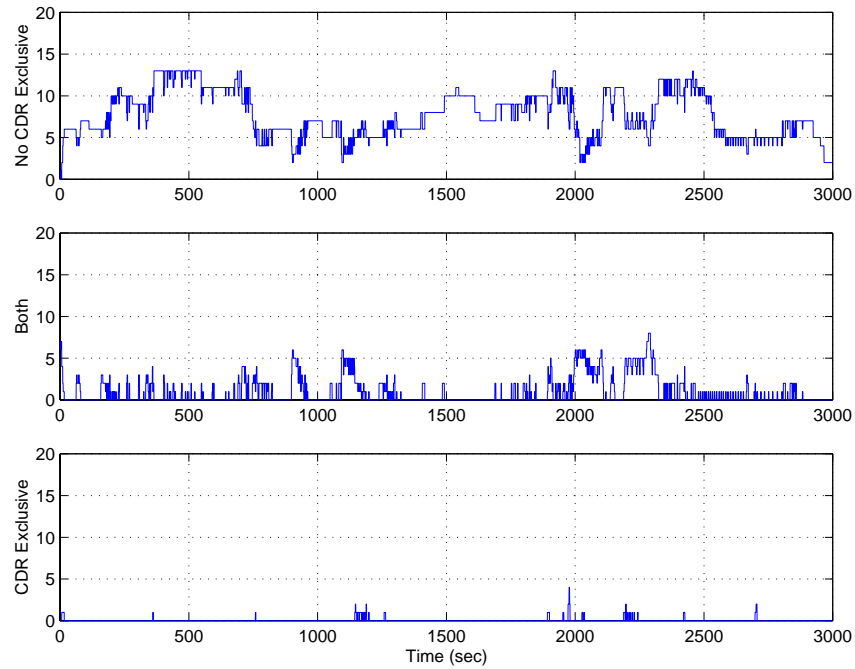


Figure 39. Ven diagram analysis of predicted conflicts for the low density case with decentralized conflict resolution.

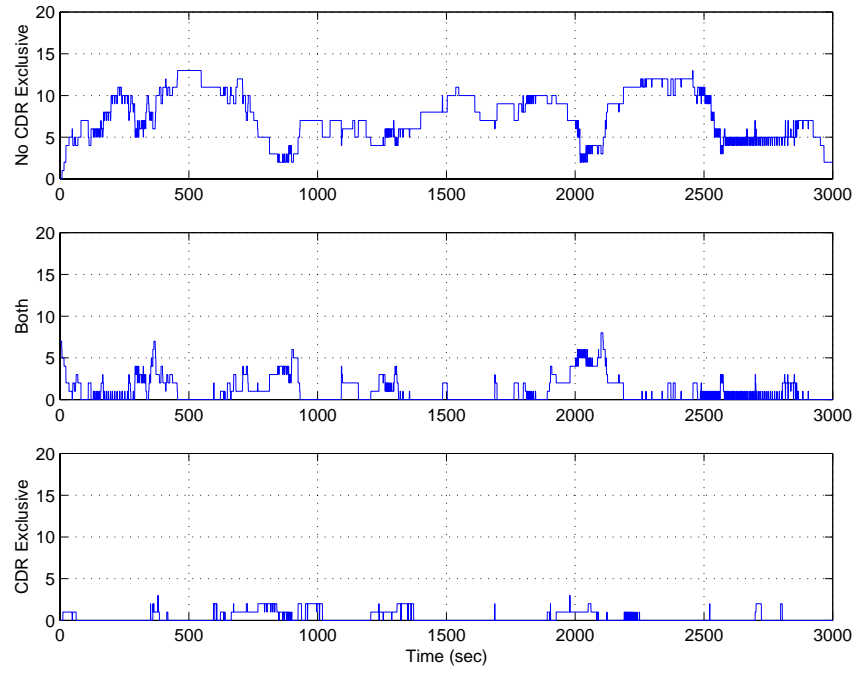


Figure 40. Ven diagram analysis of predicted conflicts for the low density case with decentralized conflict resolution with look ahead.

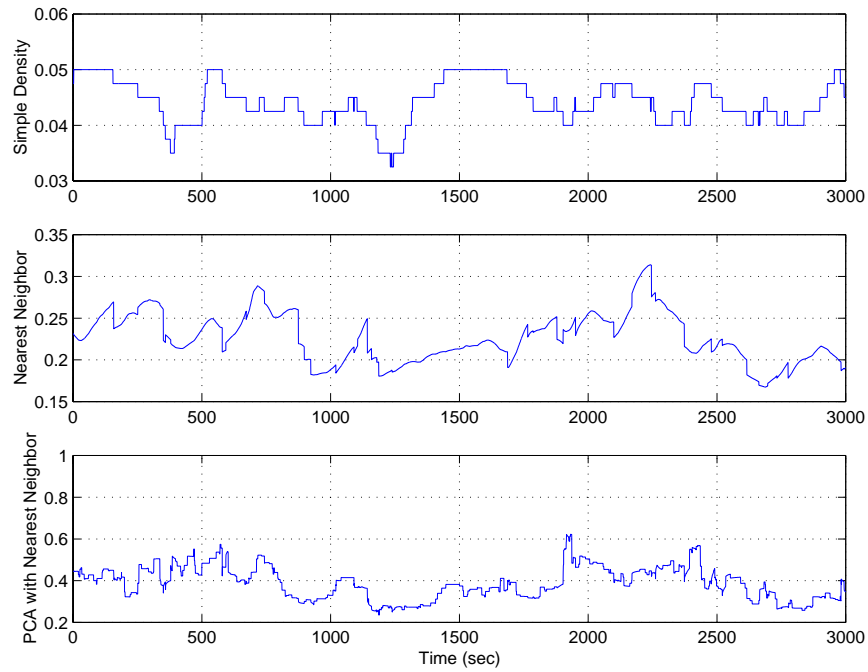


Figure 41. Dynamic density metrics of the low density case with no conflict resolution.

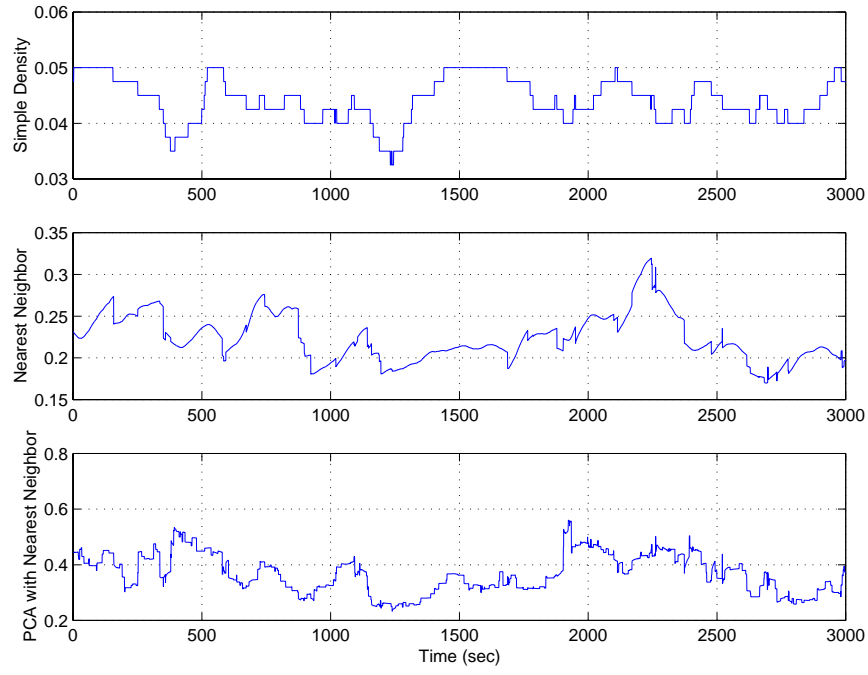


Figure 42. Dynamic density metrics of the low density case with decentralized conflict resolution.

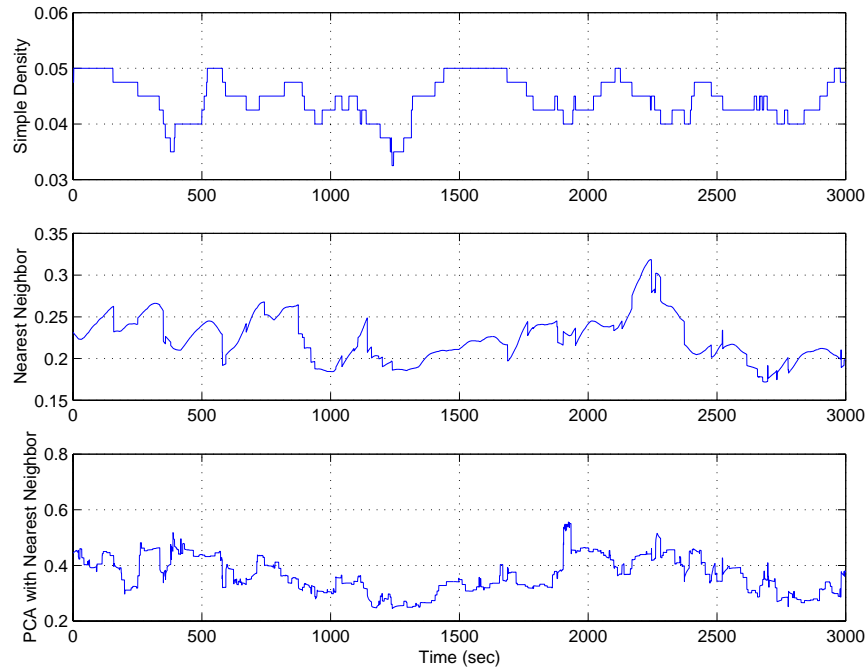
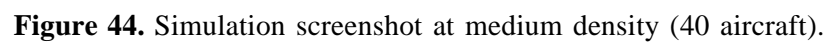


Figure 43. Dynamic density metrics of the low density case with decentralized conflict resolution with look ahead.

Next, medium density results are presented.

Next, medium density results are presented.



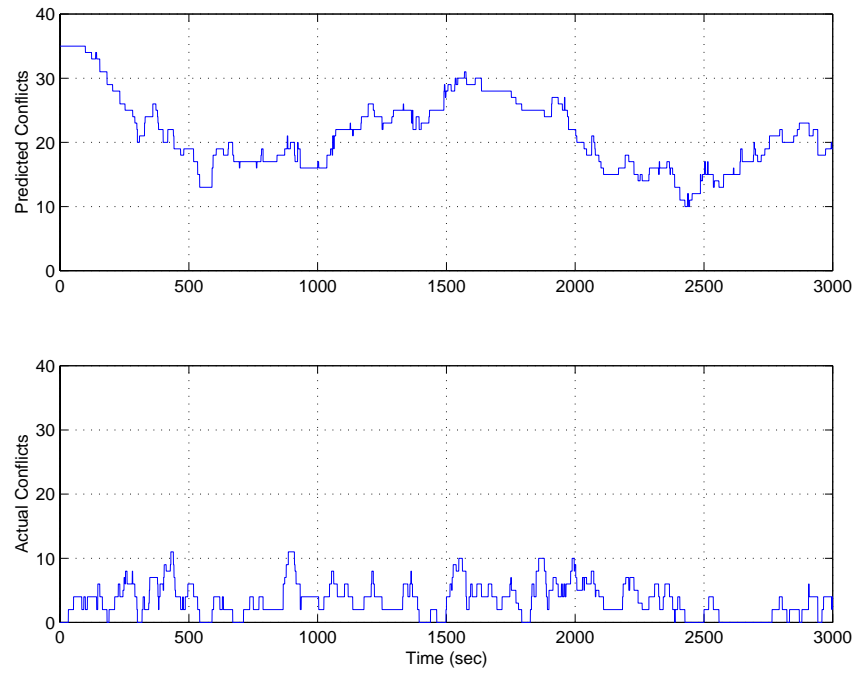


Figure 45. Predicted and actual conflicts for the medium density case with no conflict resolution.

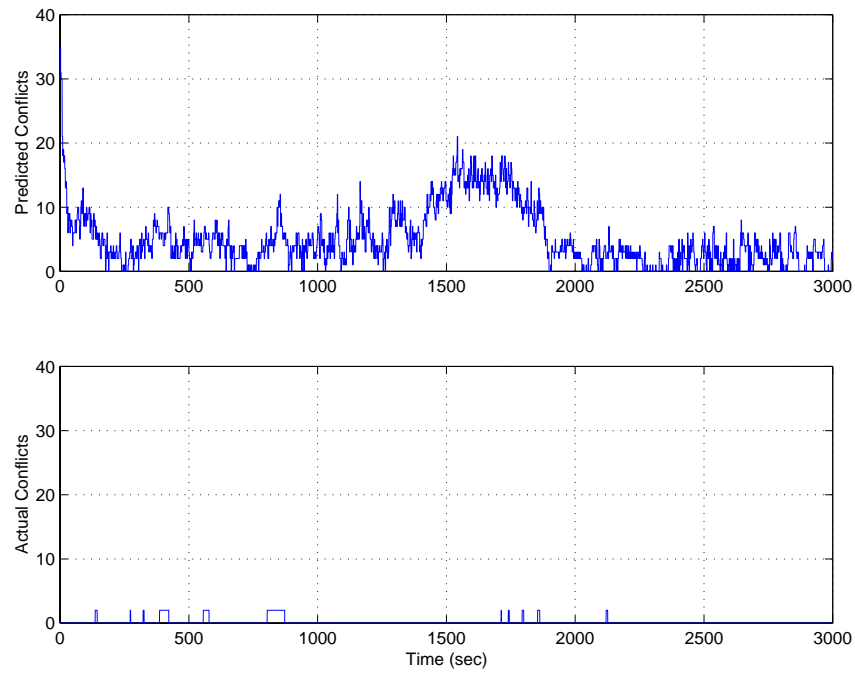


Figure 46. Predicted and actual conflicts for the medium density case with decentralized conflict resolution.

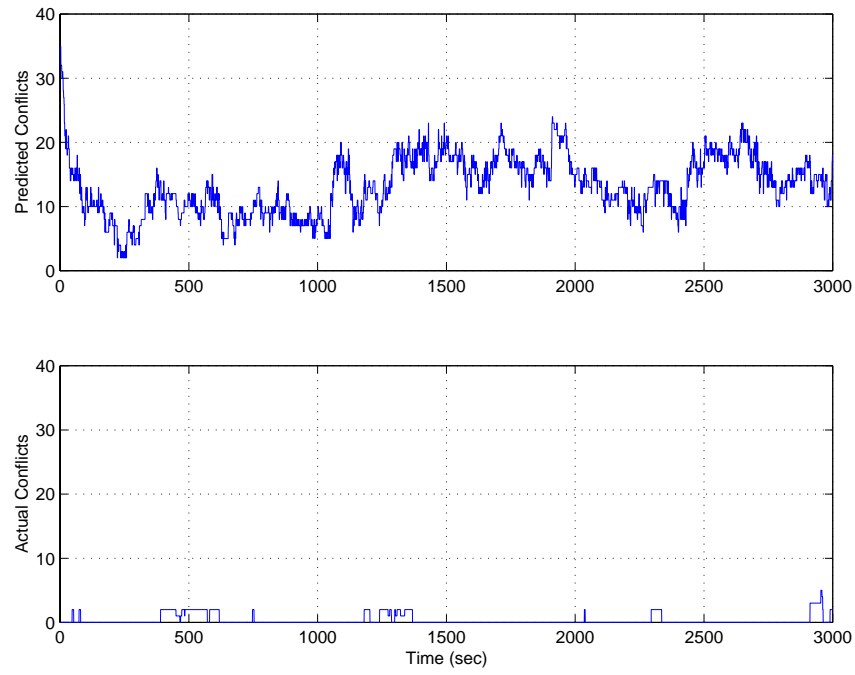


Figure 47. Predicted and actual conflicts for the medium density case with decentralized conflict resolution with look ahead.

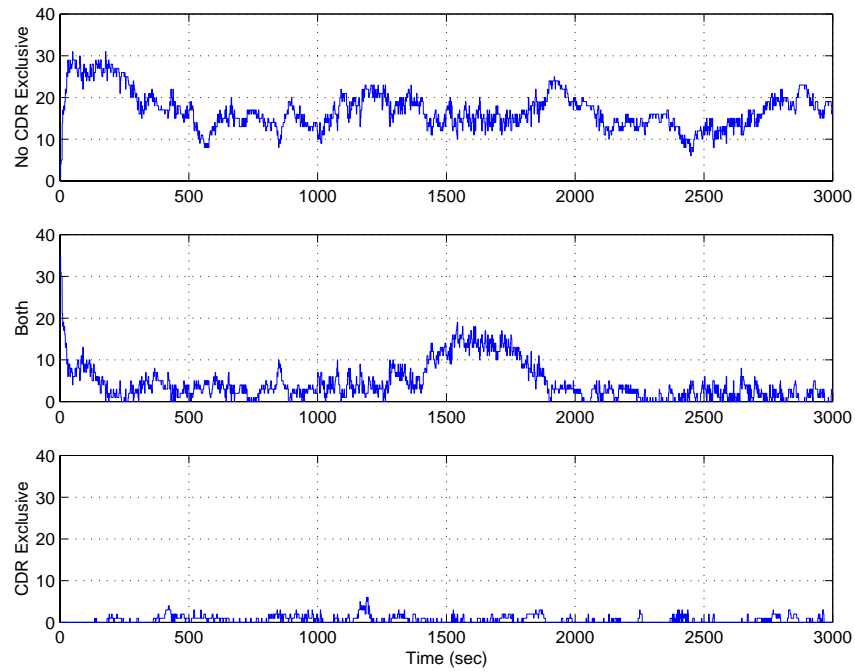


Figure 48. Ven diagram analysis of predicted conflicts for the medium density case with decentralized conflict resolution.

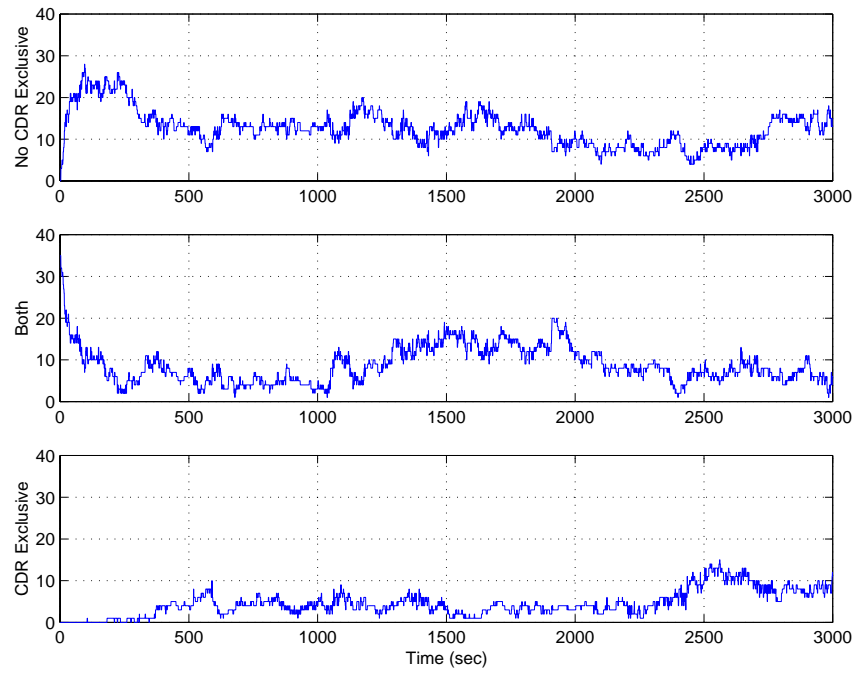


Figure 49. Ven diagram analysis of predicted conflicts for the medium density case with decentralized conflict resolution with look ahead.

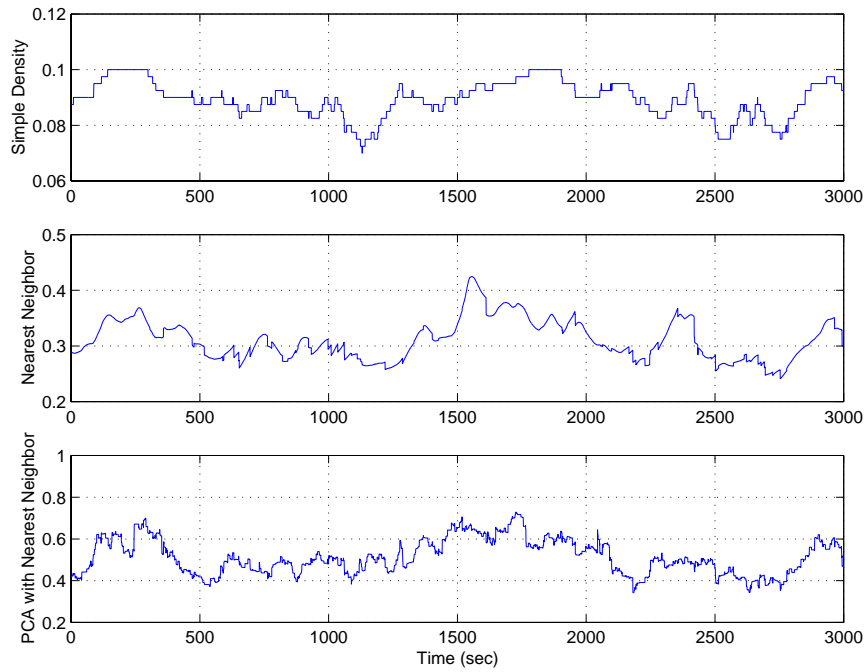


Figure 50. Dynamic density metrics of the medium density case with no conflict resolution.

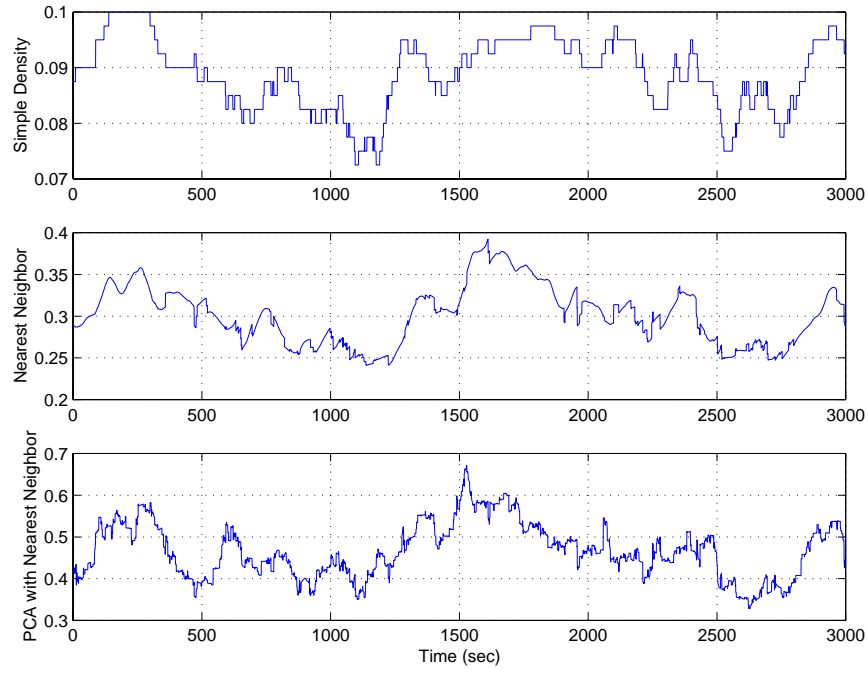


Figure 51. Dynamic density metrics of the medium density case with decentralized conflict resolution.

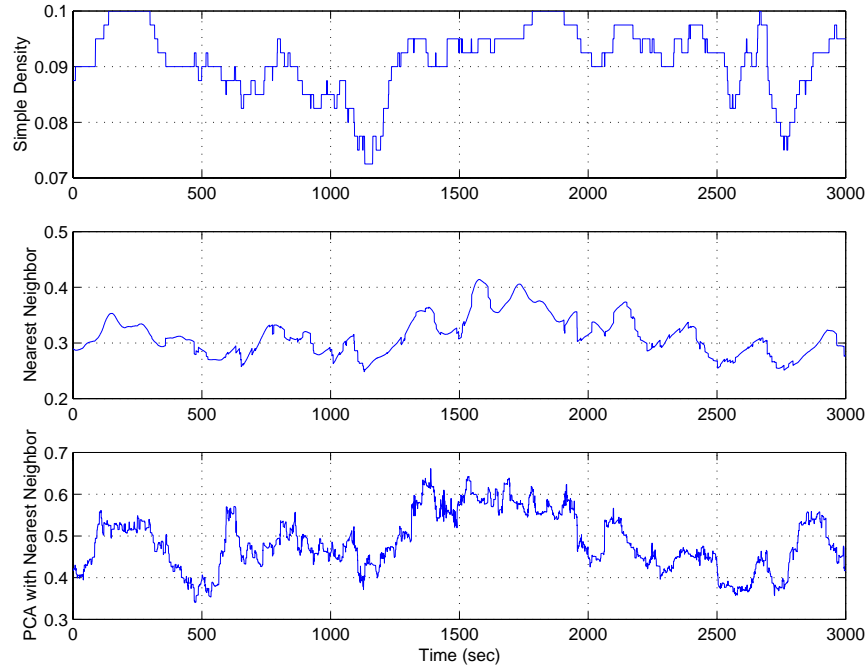
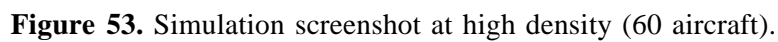


Figure 52. Dynamic density metrics of the medium density case with centralized resolution.

Next, we present example medium/high density results.

Next, we present example medium/high density results.



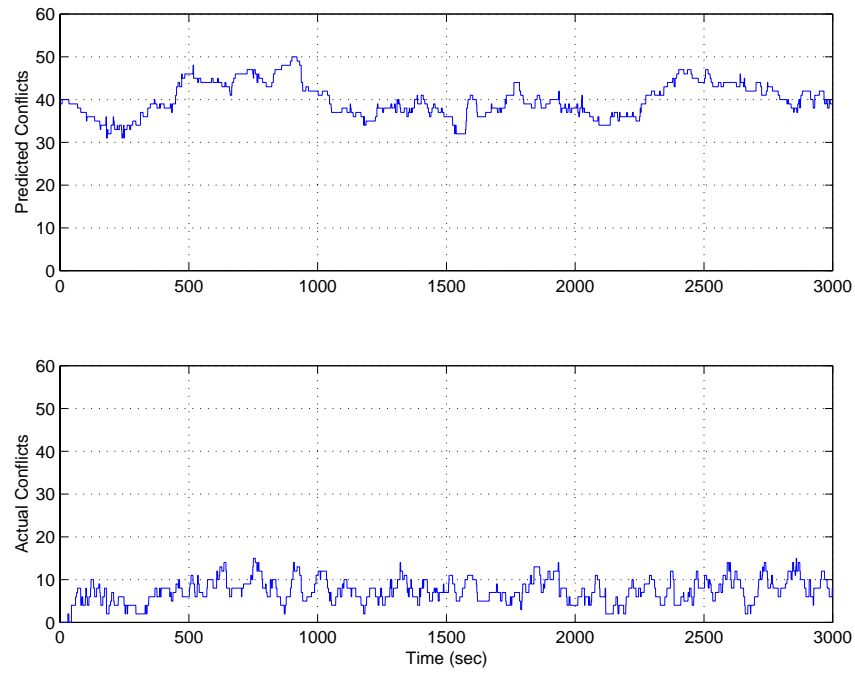


Figure 54. Predicted and actual conflicts for the high density case with no conflict resolution.

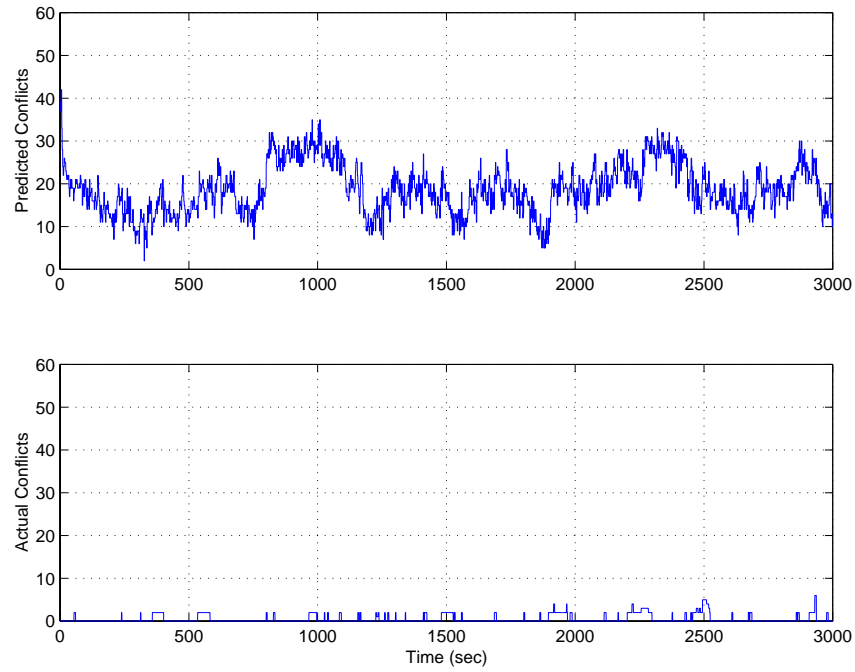


Figure 55. Predicted and actual conflicts for the high density case with decentralized conflict resolution.

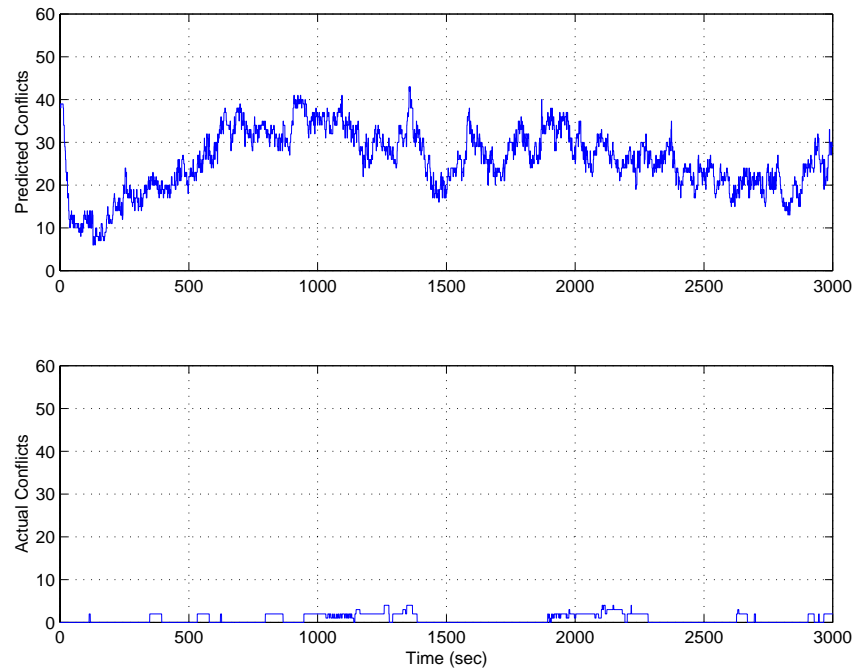


Figure 56. Predicted and actual conflicts for the high density case with decentralized conflict resolution with look ahead.

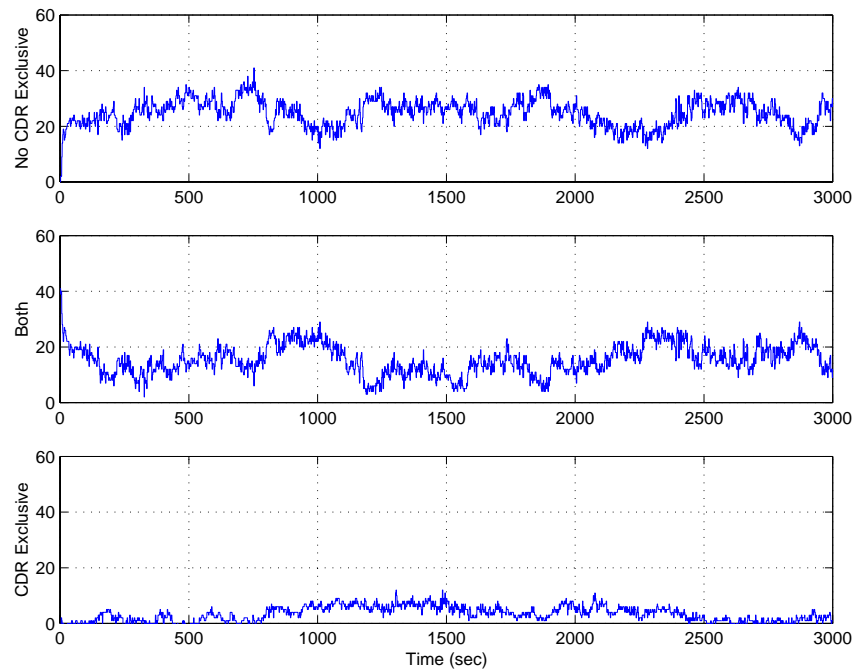


Figure 57. Ven diagram analysis of predicted conflicts for the high density case with decentralized conflict resolution.

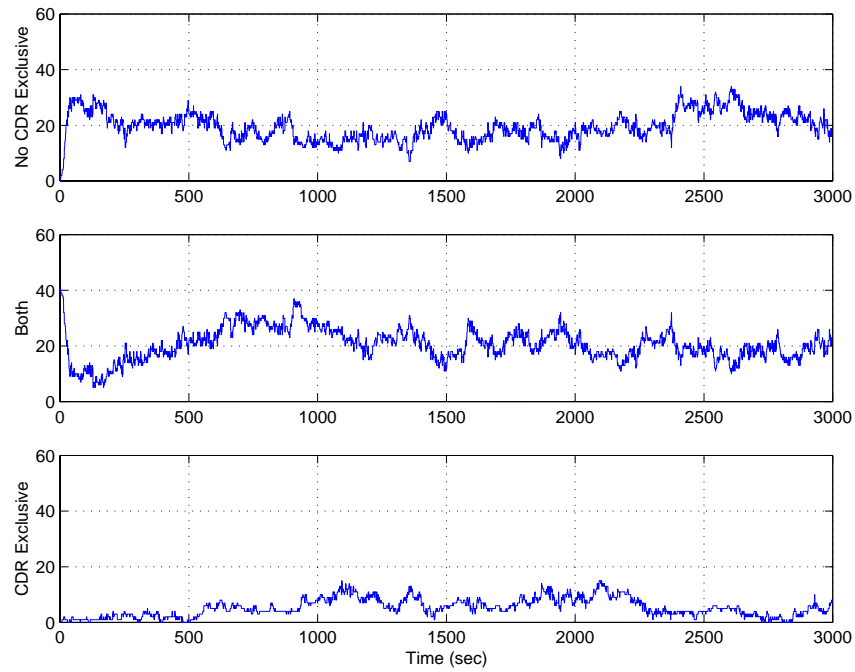


Figure 58. Ven diagram analysis of predicted conflicts for the high density case with decentralized conflict resolution with look ahead.

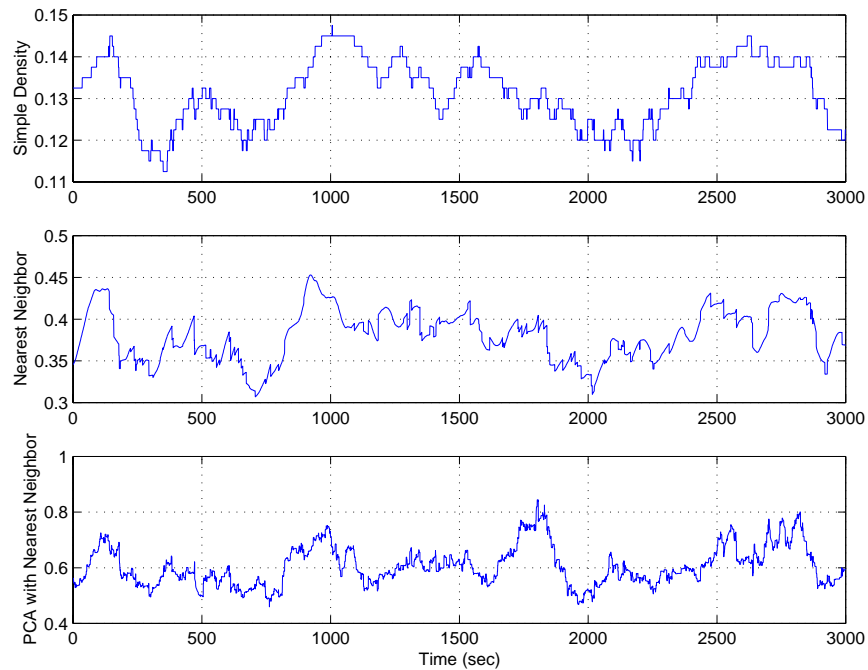


Figure 59. Dynamic density metrics of the high density case with no conflict resolution.

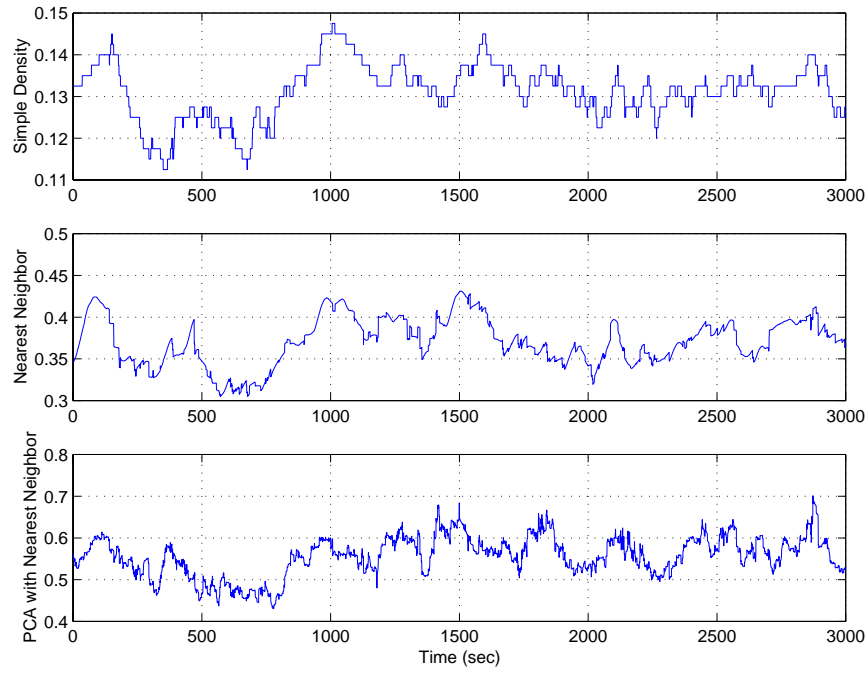


Figure 60. Dynamic density metrics of the high density case with decentralized conflict resolution.

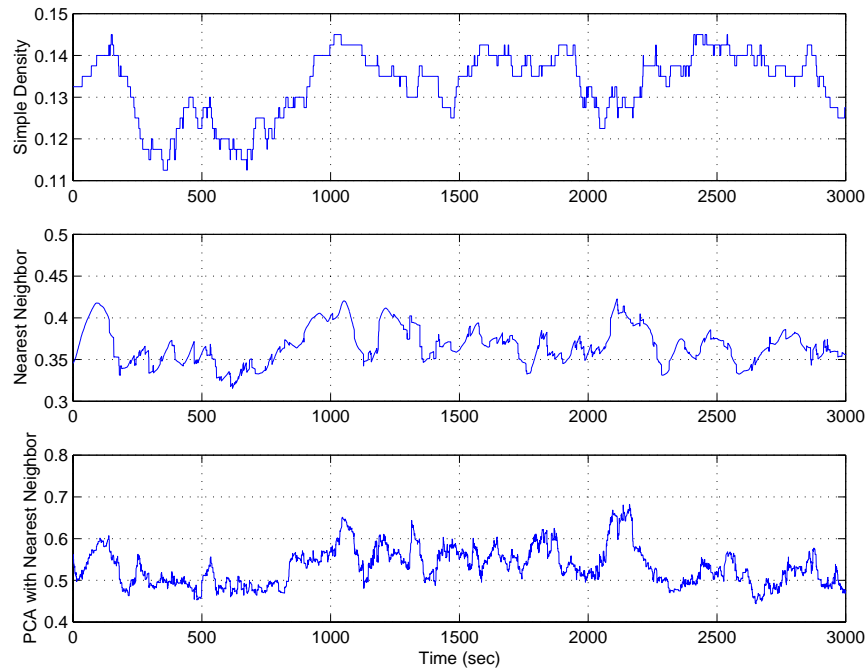


Figure 61. Dynamic density metrics of the high density case with centralized resolution.

6.4 High Density

Finally, we present the high density simulation results.

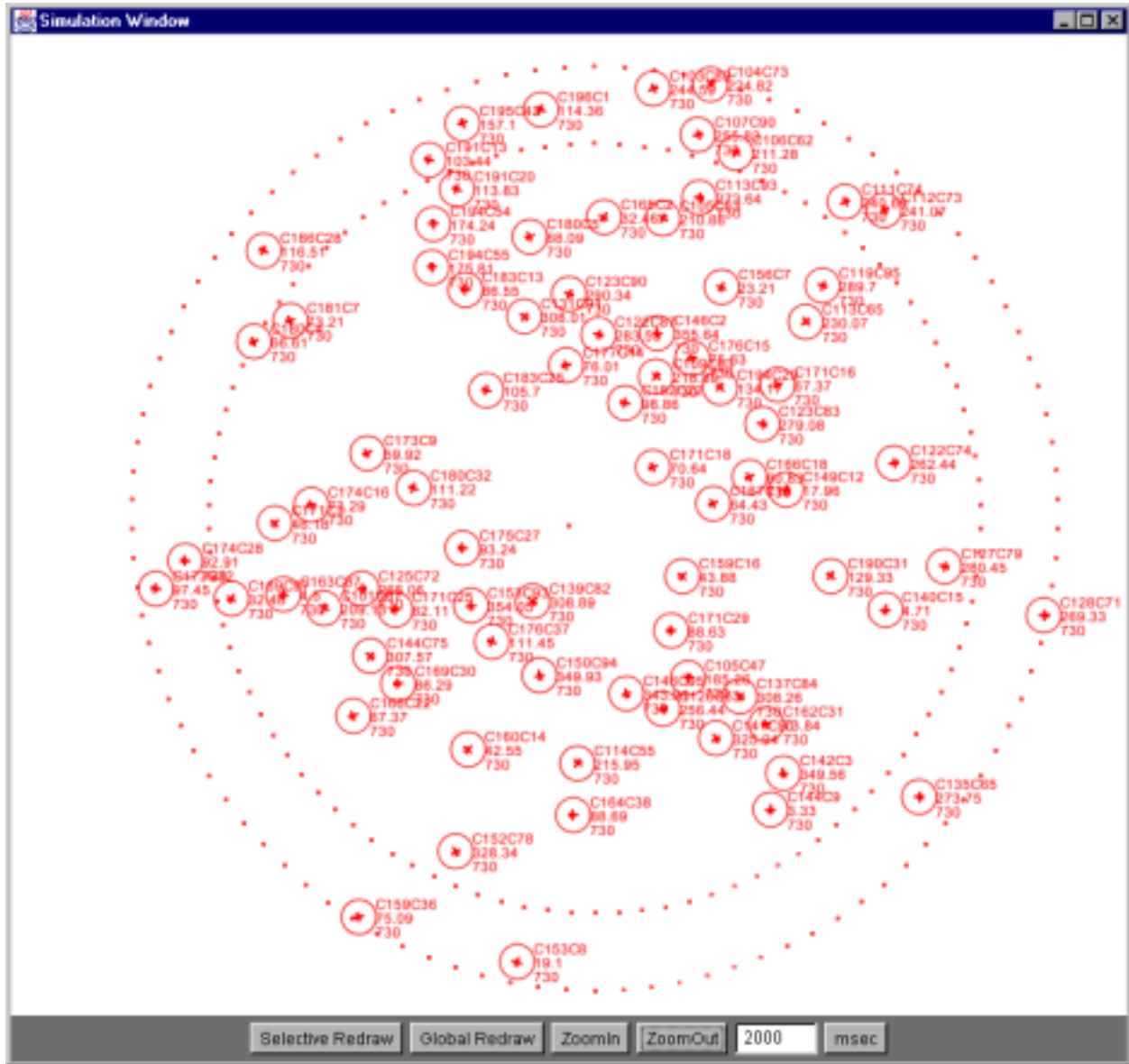


Figure 62. Simulation screenshot at high density (80 aircraft).

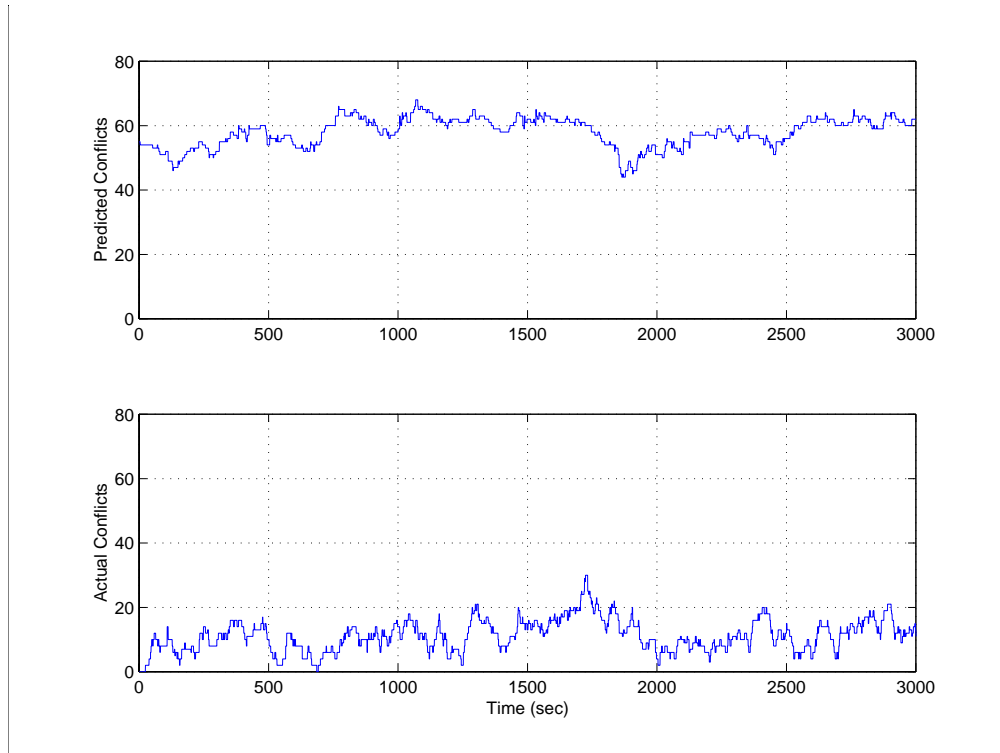


Figure 63. Predicted and actual conflicts for the high density case with no conflict resolution.

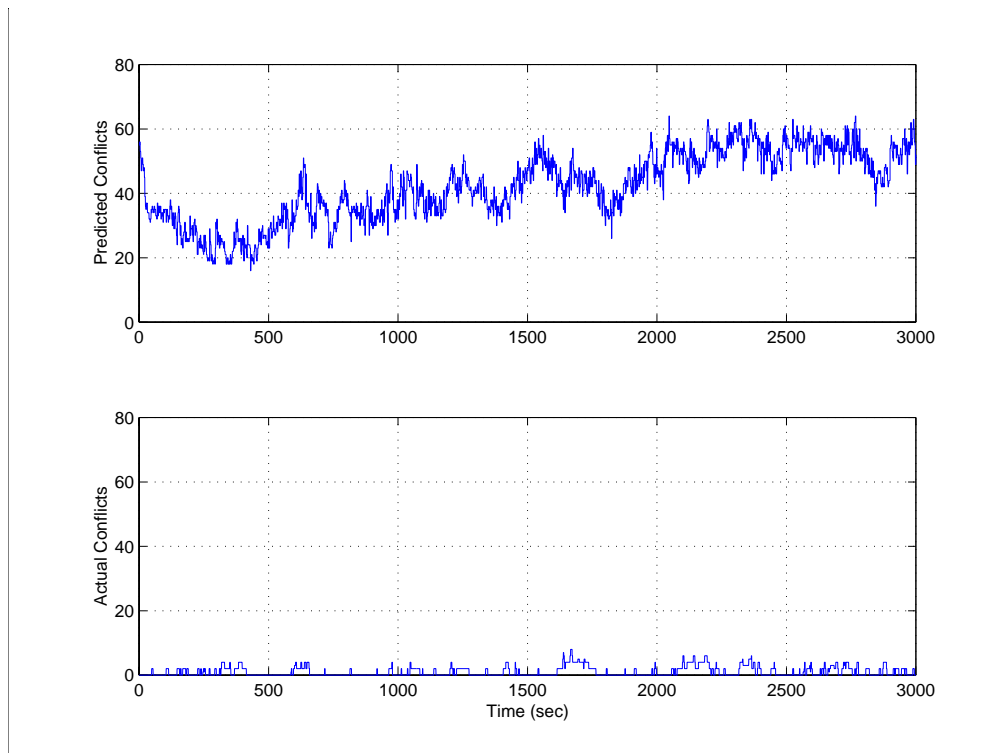


Figure 64. Predicted and actual conflicts for the high density case with decentralized conflict resolution.

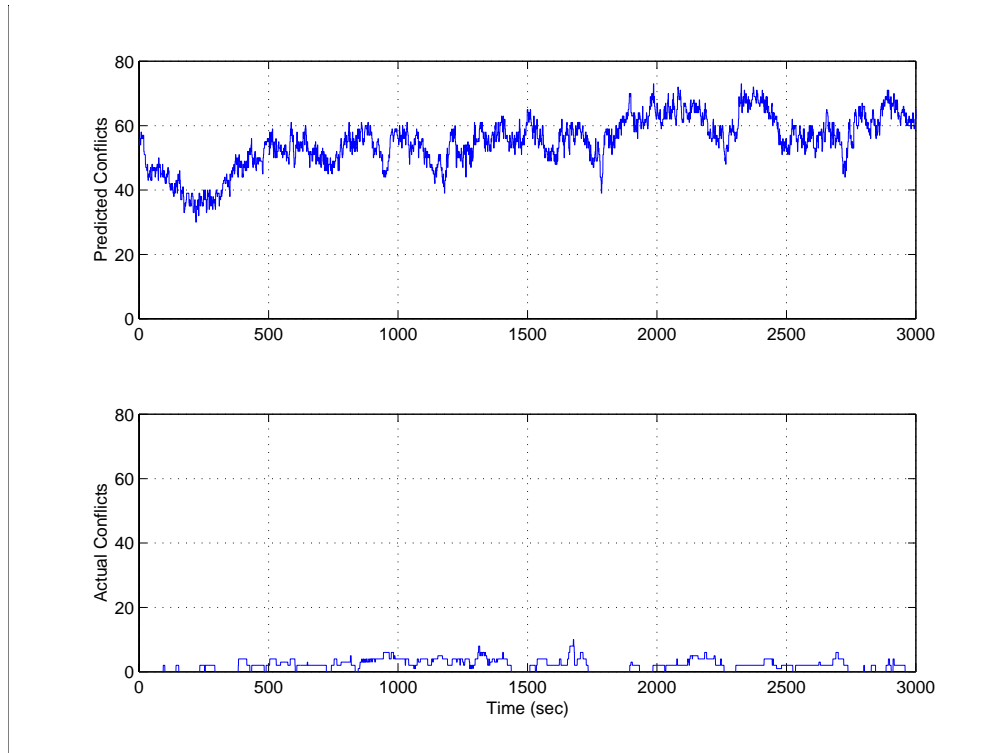


Figure 65. Predicted and actual conflicts for the high density case with decentralized conflict resolution with look ahead.

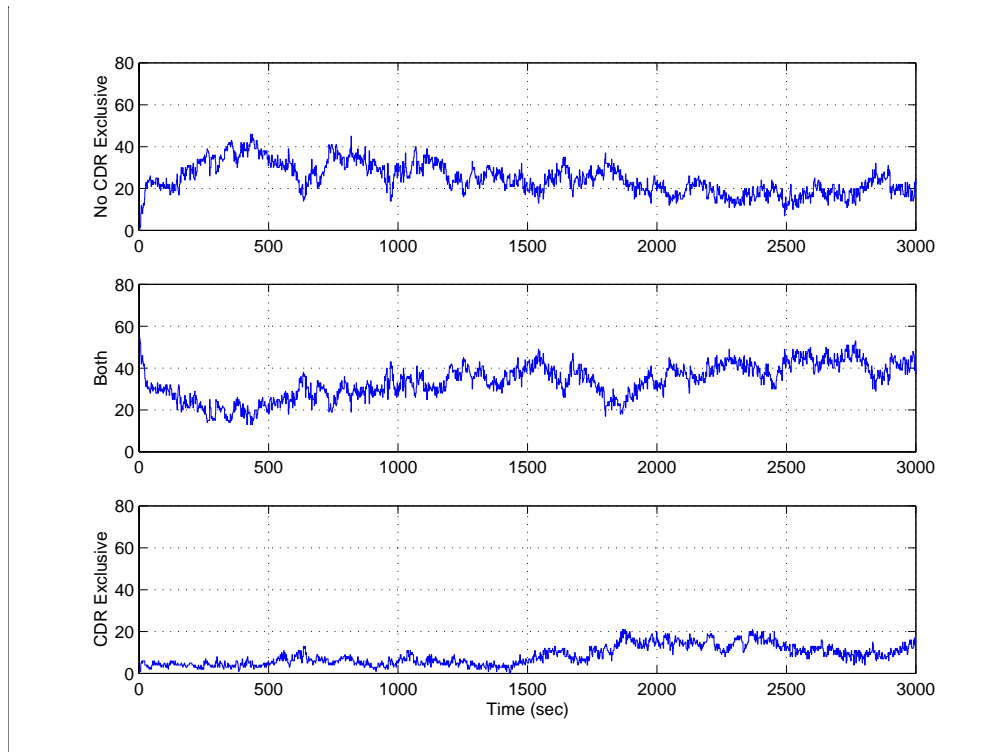


Figure 66. Ven diagram analysis of predicted conflicts for the high density case with decentralized conflict resolution.

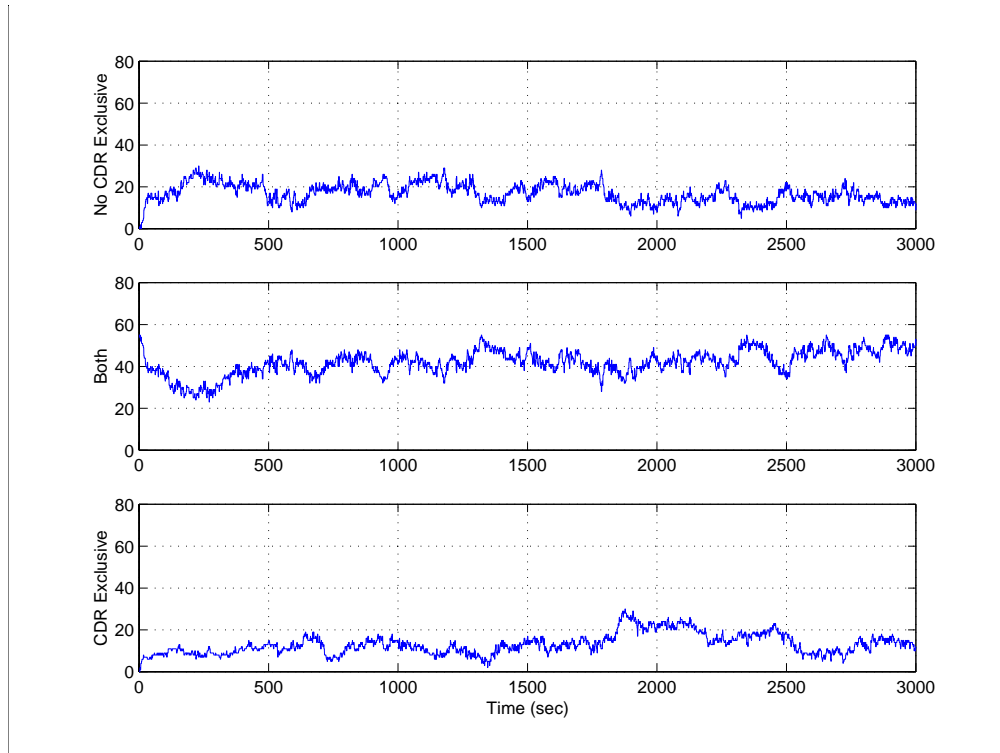


Figure 67. Ven diagram analysis of predicted conflicts for the high density case with decentralized conflict resolution with look ahead.

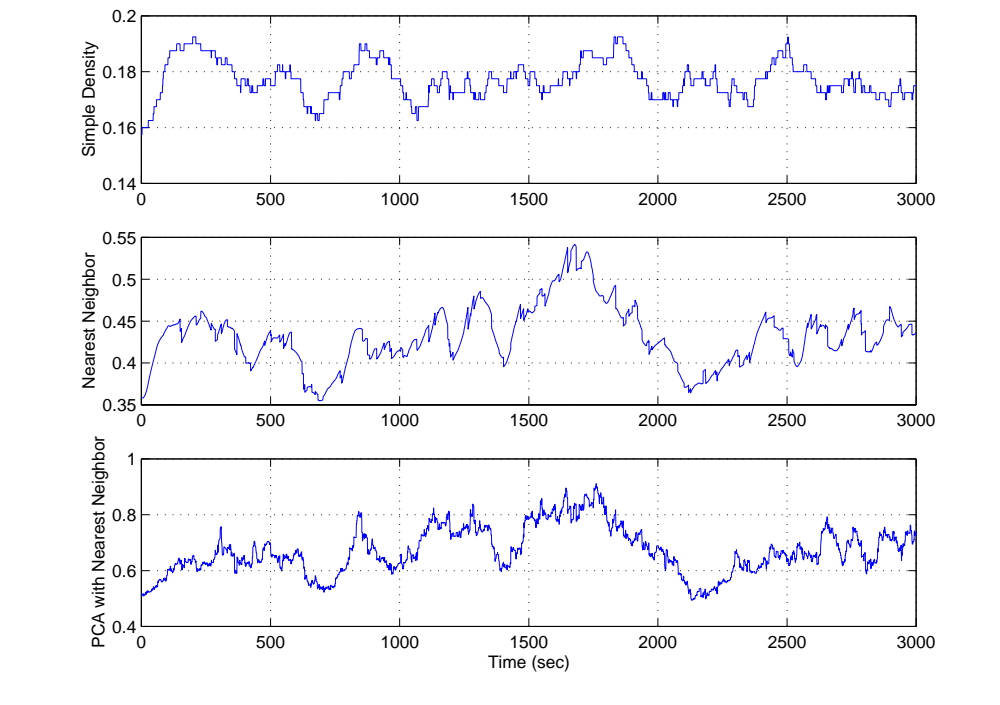


Figure 68. Dynamic density metrics of the high density case with no conflict resolution.

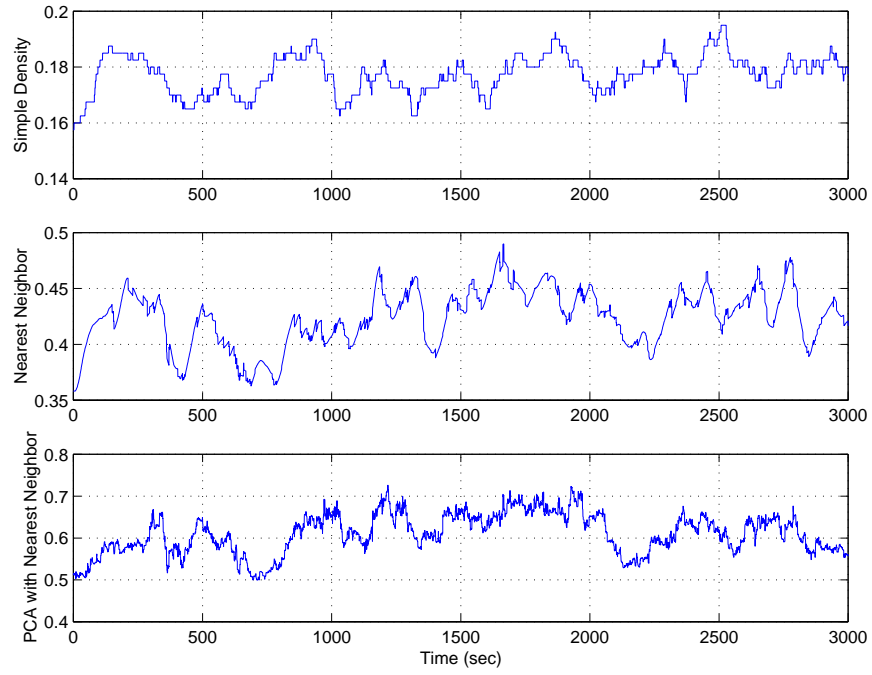


Figure 69. Dynamic density metrics of the high density case with decentralized conflict resolution.

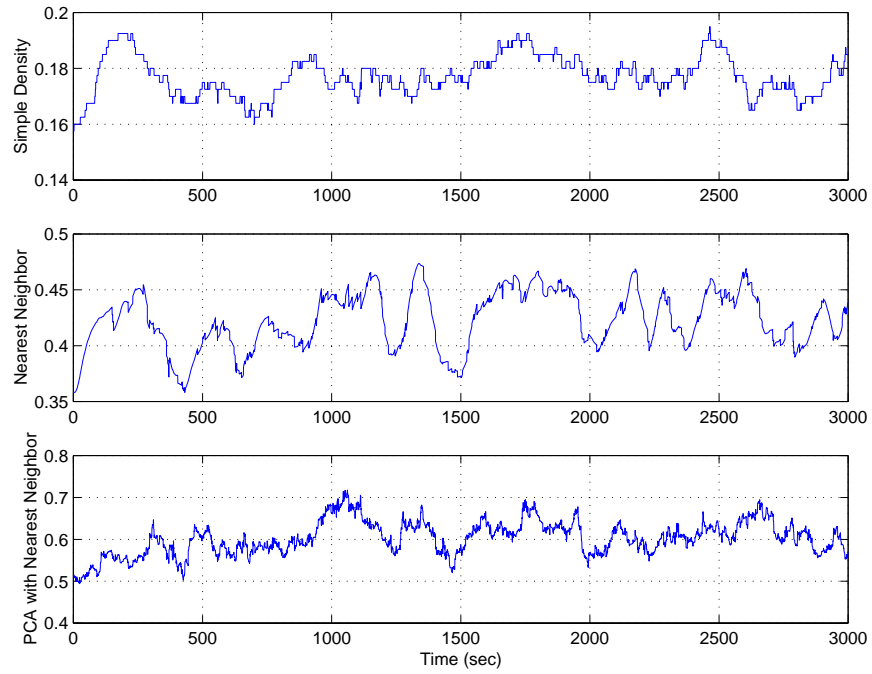


Figure 70. Dynamic density metrics of the high density case with centralized resolution.

There are several observations which can be made from the instantaneous properties. The first observation is that the decentralized control strategy will reduce the number of conflict alerts and conflicts at both low and high dynamic density levels. Thus, the resolution algorithm does not ever act to destabilize the system, nor to trigger a chaotic situation where the number of conflict alerts exponentially rise until all or many aircraft are in a conflict alert. This is an important result because it demonstrates that employing a decentralized approach will not likely make the overall situation worse.

However, the decentralized approach also does not guarantee that *all* conflicts will be avoided. This is true at any aircraft density level. In fact, the types of situations which cause poor stability performance for the decentralized approach is much more a function of the initial orientation of the aircraft in conflict rather than the overall system density or dynamic density. This indicates to us that the definition of dynamic density may need to encapsulate such orientations to be useful. Of course, a high dynamic density increases the likelihood of such conflicts appearing.

The two resolution algorithms experimented with were very similar. The only difference between the algorithms was that the “look ahead” algorithm was able to evaluate a resolution maneuver for outside constraints. Surprisingly, this additional feature reduced the algorithms effectiveness. Finally, intense scrutiny of the problem showed that the algorithm would make poor choices and vector aircraft in a sub-optimal sense in an effort to avoid a constraint aircraft that was not nearly as much as a concern as the immediate conflict. Sometimes the sub-optimal solution would take the aircraft into a tactical situation which could not be resolved. Furthermore, the “look-ahead” algorithm would switch cases on whether or not to fly the optimal or sub-optimal solution. This chattering itself sometimes lead to a conflict situation. Therefore, the less informed algorithm, which always vectored aircraft using the optimal solution in spite of any additional conflicts caused with neighboring constraint aircraft, had better performance because it committed to a solution early and let constraint aircraft deal with their own conflicts. The lesson learned was that using additional information does not necessarily yield better system performance.

From our observations, it is clear that more intelligent algorithms are required to handle some of the difficult multi-aircraft conflicts that are encountered in unstructured Free Flight scenarios. Such an approach might involve the following steps:

1. Define a cluster of aircraft. This cluster would contain not only the multiple n conflict aircraft but also any constraint aircraft nearby. This identification of a cluster allows for an n -body CD&R problem to be solved on a small set of aircraft (e.g., $n=3$ or $n=4$) rather than trying to solve the entire N -body problem associated with all N aircraft in the simulation.
2. Try not to involve any constraint aircraft in the CD&R solution. In this way, the constraint aircraft should be allowed to fly their Free Flight paths without being involved in the conflict resolution maneuvering; they are involved in the CD&R problem because they will define constraints to the available airspace to solve the n -body problem.
3. Localize the problem so that non-cluster aircraft are not involved. A successful decentralized CD&R solution to the problem will solve the problem within the cluster, and not allow the maneuver paths to affect the constraint aircraft nor other aircraft outside the cluster. If this is not the case, then the CD&R algorithm will need to increase the size of the cluster by adding those nearby aircraft that are affected.

The algorithms that we implemented did not identify “tactical alert zones” [KMH96], which are regions where no maneuver can help avoid a conflict. Rather, sub-optimal solutions would attempt to solve the conflict resolution problem but fail due to turn dynamics or lack of time to complete the maneuver. To correct this problem, if a tactical alert zone is encountered, the solution that passes within this zone should not be considered a valid solution, even if a constraint aircraft exists and may have to move out of the way.

One limitation of the instantaneous property analysis is that it does not yield a good measure of the domino effect. It is true that we observe a stable system since the predicted and actual conflicts are greatly reduced with resolution as opposed to no-resolution. However, this can be misleading. When the scenario runs in the no-resolution mode, conflicts are detected, but no maneuver is initiated to avoid them. Therefore, the conflict alerts persist in time and cascade into a large number, only to

recede as conflicts go through their full course. With the resolution algorithms running and attempting to address predicted conflicts, the number of instantaneous conflicts comes down just by virtue of the fact that maneuvering is taking place to mitigate the conflict. However, this analysis gives us no indication of how many additional aircraft may have been involved in conflicts because of conflict resolution strategies. This is the essence of the domino effect and requires a different analysis, the cumulative analysis.

6.5 Comparison of Results

Cumulative properties from a large collection of data were analyzed to investigate the potential existence of a domino effect, stability, and performance degradation in the system. The purpose of this analysis was to see trends over time and over various density levels that would indicate stability and performance tradeoffs of the system. A total of 2304 data runs of 3000 sec each were collected. System densities varied from 5 aircraft to 80 aircraft in increments of 5 aircraft per 100 nmi² reference area. A total of 48 runs of each density were made, each with basic resolution and resolution with look-ahead. The cumulative path distance of each aircraft was collected and compared to the straight line path distance to between along the route. This was the basis for the performance metric. A measure of stability was determined by comparing the average number of conflicts encountered by each aircraft in both the no-resolution and resolution scenarios.

Figure 71 through Figure 74 illustrate the relationship between stability and performance for the systems investigated. From the results, it is clear that an increase in system density degrades both the stability and performance of the system. The number of conflicts that each aircraft sees, grows exponentially with density. Furthermore, performance is degraded, however usually the performance loss is less than 10% even for the highest densities.

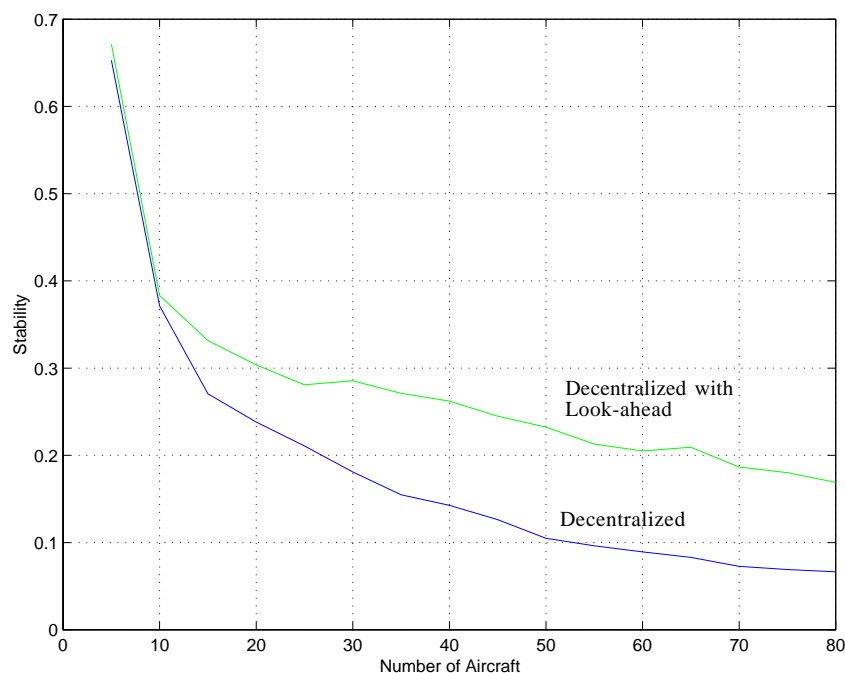


Figure 71. System stability as a function of increasing system complexity.

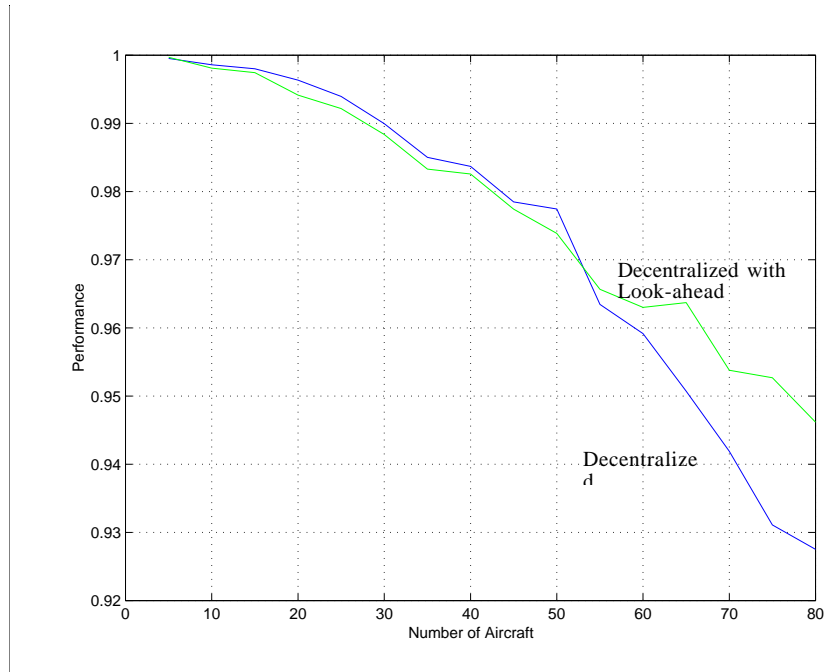


Figure 72. System Performance as a function of increasing system complexity

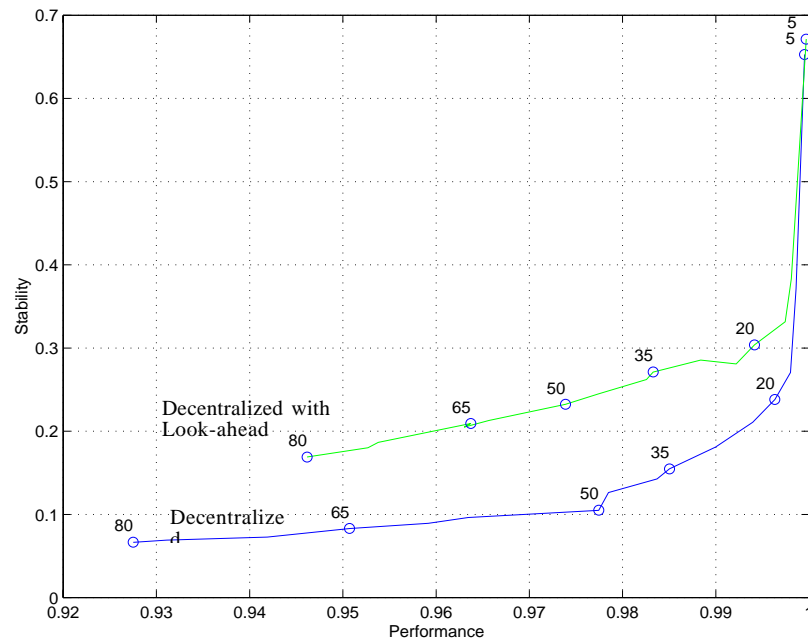


Figure 73. System Stability vs System Performance for increasing system complexity (data points are labeled with the number of aircraft within the reference area).

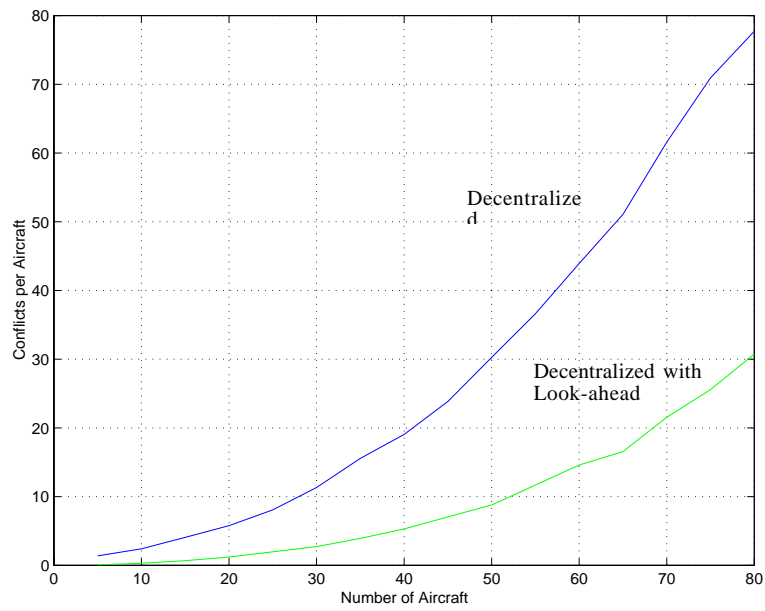


Figure 74. Plot of number of conflicts per aircraft vs the number of aircraft in the simulation

7.0 CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusions and recommendations which we have drawn from both the literature survey and simulation results.

7.1 Conclusions

Our literature review of methods for decentralized control techniques revealed several promising techniques applicable to DAG TS.

The trade-off study identified the top three candidates to be:

1. Hierarchical Control – since it forms the structure of a high level ATM working with a lower level ATC system
2. Distributed Control – since the ATC system is designed to be spatially distributed to those airspace locations where clusters of aircraft form conflicts
3. Principled Negotiation – since it provides the mechanism for user preferences to be taken into account and conflict detection and resolution to be achieved autonomously or with humans in the loop.

All of the above methods allow for scalability as the NAS grows. A distributed control system technique was modeled and simulations were performed to demonstrate the DAG TS concept; the results indicate a feasible combination.

We presented results from the study of two decentralized control strategies applicable to a DAG TS problem. The air traffic management problem models a future Free Flight paradigm for air traffic operations, where aircraft are allowed to fly in any direction according to their own user preferences. The primary research issue addressed was the trade-off between the system stability and performance of the decentralized systems investigated. A stability definition was motivated by the potential for a “domino effect”, where we identify aircraft that are nearby a conflict and experience a trajectory interruption due to a conflict resolution maneuver. Through our experiments, we noticed that the domino effect does not reveal any significant system stability information for high densities. This is because a high density airspace usually results in so many conflicts that the number of additional undisturbed aircraft for which the domino effect can propagate is small. Instead of focusing on modeling stability based on a parameter for the domino effect, the predominant stability parameter was determined to involve a ratio between two sets:

- S_1 : The total number of conflict alerts that occur for the set of aircraft that experience conflict alerts when no conflict resolution algorithms are implemented, and
- S_2 : The total number of conflict alerts that occur for the set of aircraft that experience conflict alerts when no conflict resolution algorithms are implemented.

The data reveal that the decentralized control strategies have reduced stability and reduced performance as the dynamic density increases. While performance is degraded, however, usually the performance loss is less than 10% even for the highest densities.

The data reveal a trend that number of conflict alerts that each aircraft experiences grows exponentially with density. In today’s positive control air traffic control system, such a growth in the number of conflict alerts would cause unmanageable workload for air traffic controllers. With aircraft (pilots) addressing these conflicts in a distributed manner, as simulated in this study, the conflicts are manageable for smaller densities and medium densities, with only a few actual conflicts occurring at high densities. Although the decentralized strategies eventually had Protected Airspace Zone conflicts at higher dynamic densities, the numbers were not large (usually isolated 2 or 3 aircraft conflict with up to 40 to 70 aircraft systems), which we presume would be corrected by air traffic controller intervention into Free Flight. There were no observations of chaotic effects that might cause an air traffic controller to be unable to intervene.

7.2 Recommendations

This study indicates that a decentralized conflict resolution scheme can be used to reduce the number of aircraft conflicts in a crowded airspace. However, we have also demonstrated that a decentralized approach does not guarantee that no conflicts will ever occur. Therefore we recommend that the decentralized technique should be part of a hierarchical control system wherein a supremal controller would provide guidance and intervention in the cases where the decentralized, distributed control technique degrades. In the future, a comparison of several conflict detection and resolution methods being coordinated by a supremal controller in the form of a hierarchical distributed control system should be performed to investigate and quantify the system benefits of such techniques for DAG TS.

This report has also presented several metrics to measure the system complexity, performance, and stability. However, more work is needed to determine what combination of these metrics will allow for the best evaluation of conflict situations and resolution techniques. Specifically, we recommend more analysis to determine sound correlation between system complexity and the likelihood of conflicts. Furthermore, parameters should be developed that will better indicate a “domino effect” in the form of an additional level of complexity added to a system caused by the resolution algorithm itself.

8.0 REFERENCES

- [AH97] Andrews, J.W., and Hollister, W.M., "Impact of Intent-Based Maneuver Constraints on Alert Rates," *Air Traffic Control Quarterly*, Vol. 5, No. 3, pp. 157-179, 1997.
- [A89a] Arbib, M.A., "Neuroscience in Motion: The Application of Schema Theory to Mobile Robots," in *Visuomotor Coordination*, J-P Ewert and M.A. Arbib (Eds.), Plenum Press, New York, NY, 1989.
- [A89b] Arkin, R.C., "Motor Schema-Based Mobile Robot Navigation," *Intern. Journal of Robotics Research*, Vol. 8, No. 4, pp. 92-112, Aug., 1989.
- [A89c] Arkin, R.C., "Navigation Path Planning for a Vision-Based Mobile Robot," *Robotica*, Vol. 7, pp. 49-63, 1989.
- [A89d] Arkin, R.C., "Three-Dimensional Motor Schema Based Navigation," *Proc. of the NASA Conf. on Space Telerobotics*, Vol. 1, G. Rodriguez and H. Seraji (Eds.), Pasadena, CA pp. 291-299, Jan., 1989.
- [A90] Arkin, R.C., "The Impact of Cybernetics on the Design of a Mobile Robot System: A Case Study," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 20, No. 6, pp. 1245-1257, Nov./Dec., 1990.
- [A98] Arkin, R.C., *Behavior-Based Robotics*, MIT Press, Cambridge, MA, 1998.
- [AA93] Astrom, K.J., and Arzen, K.E., "Expert Control," in *An Introduction to Intelligent and Autonomous Control*, P.J. Antsaklis and K.M. Passino, Eds., Kluwer Academic Pub, Boston, MA, pp 163-189, 1993.
- [AB98] Arkin, R.C. and Balch, T., "Cooperative Multiagent Robotic Systems," *Artificial Intelligence and Mobile Robots*, D. Kortenkamp, R.P. Bonasso, and R. Murphy (eds), MIT Press, Cambridge, MA, 1998.
- [AHS96] Alur, R., Henzinger, T.A., and Sontag, E.D., Eds., *Hybrid Systems III*, Lecture Notes in Computer Science, Vol. 1066, Springer-Verlag, New York, NY, 1996.
- [AKL99] Antsaklis, P., W. Kohn, W., M. Lemmon, M., A. Nerode, N., S. Sastry, S., Eds., *Hybrid Systems V*, Lecture Notes in Computer Science, Vol. 1567, Springer-Verlag, , New York, NY, 1999.
- [AKMO97] Adams, M., Kolitz, S., Milner, J., and Odoni, A., "Evolutionary Concepts for Decentralized Air Traffic Flow Management," *Air Traffic Control Quarterly*, Vol. 4, No. 4, pp. 281-306, 1997.
- [AKNS95] Antsaklis, P., Kohn, W., Nerode, A., and Sastry, S., Eds., *Hybrid Systems II*, Lecture Notes in Computer Science, Vol. 999, Springer-Verlag, New York, NY, 1995.
- [AKNS97] Antsaklis, P., Kohn, W., Nerode, A., Sastry, S., Eds., *Hybrid Systems IV*, Lecture Notes in Computer Science, Vol. 1273, Springer-Verlag, New York, NY, 1997.
- [AKO96] Adams, M., Kolitz, S., and Odoni, A., "Evolutionary Concepts for Decentralized Air Traffic Flow Management," *AIAA Guidance, Navigation, and Control Conf.*, San Diego, CA, July, 1996.
- [An89] Anderson, T.L., *A Reflexive Behavioral Approach to the Control of a Mobile Robot*, M.S. Thesis, Univ. of Minnesota, May, 1989.
- [An96] Anon., *An Evaluation of Air Traffic Control Complexity*, Final Report, NASA Contract No. NAS2-14284, Wyndemere Corp, Boulder, CA, Oct., 1996.
- [ASY96] Alligood, K.T., Sauer, T.D., and Yorke, J.A., *Chaos: An Introduction to Dynamical Systems*, Springer-Verlag, New York, NY, 1996.
- [BA94] Balch, T., and Arkin, R.C., "Communication in Reactive Multiagent Robotic Systems," *Autonomous Robots*, Vol. 1, pp. 1-25, 1994.
- [BA98] Balch, T., and Arkin, R.C., "Behavior-Based Formation Control for Multi-Robot Teams," *IEEE Trans. on Robotics and Automation*, Vol. 14, No. 6, December, 1998.
- [BB96] Balakrishnan, S.N. and Biega, V., "Adaptive-Critic-Based Neural Networks for Aircraft Optimal Control," *Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 4, pp. 893-898, July-Aug., 1996.

- [BLM00] Bilimoria, K., Lee, H.Q., Mao, Z-H, and Feron, E., "Comparison of Centralized and Decentralized Conflict Resolution Strategies for Multiple-Aircraft Problems," *AIAA Guidance, Navigation, and Control Conf.*, Denver, CO, Aug., 2000.
- [BSL00] Bilimoria, K., Sheth, K.S., Lee, H.Q., and Grabbe, S.R., "Performance Evaluation of Airborne Separation Assurance for Free Flight," *AIAA Guidance, Navigation, and Control Conf.*, Denver, CO, Aug., 2000.
- [BBM98] Branicky, M.S., Borkar, V.S., and Mitter, S.K., "A Unified Framework for Hybrid Control: Model and Optimal Control Theory," *IEEE Trans. on Automatic Control*, Vol. 43, No. 1, pp. 31-45, Jan., 1998.
- [BC86] Blidberg, D.R. and Chappel, S.G., "Guidance and Control Architecture for the EAVE Vehicle," *IEEE Journal of Oceanic Engineering*, Vol. OE-11, No. 4, pp. 449-461, Oct., 1986.
- [BCW99] Beatty, R., Corwin, B., and Wambsganss, M., "Collaborative Decision-Making: A Success Story of an Airline-FAA Partnership," *10th Intern. Conf. on Aviation Psychology*, Columbus, OH, May, 1999.
- [Bee90] Beer, R.D., *Intelligence as Adaptive Behavior*, Academic Press, New York, NY, 1990.
- [Ber93] Berenji, H.R., "Fuzzy and Neural Control," in *An Introduction to Intelligent and Autonomous Control*, P.J. Antsaklis and K.M. Passino, Eds., Kluwer Academic Pub, Boston, MA, pp 215-236, 1993.
- [BL93] Berenji, H.R., Lea, R.N., Jani, Y., Khedkar, P., Malkani, A., and Hoblit, J., "Space Shuttle Attitude Control by Reinforcement Learning and Fuzzy Logic," *2nd IEEE Intern. Conf. on Fuzzy Systems*, San Francisco, CA, pp 1396-1401, March/April, 1993.
- [BPC94] Blaasvaer, H., Pirjanian, P., and Christensen, H.I., "AMOR – An Autonomous Mobile Robot Navigation System," *IEEE Conf. on Systems, Man, and Cybernetics*, San Antonio, TX, pp. 2266-2271, Oct., 1994.
- [Br86a] Brooks, R.A., "A Robust Layered Control System For A Mobile Robot," *IEEE Journal of Robotics and Automation*, Vol. RA-2, No. 1, pp. 14-23, March, 1986.
- [Br86b] Brooks, R.A., *Achieving Artificial Intelligence Through Building Robots*, A.I. Memo 899, Artificial Intelligence Laboratory, M.I.T., May, 1986.
- [Bra97] Branicky, M.S., "Stability of Hybrid Systems: State of the Art," *Proc. of the 36th IEEE CDC*, San Diego, CA, Dec., 1997.
- [BS93] Belkin, B.L., and Stengel, R.F., "AUTOCREW: A Paradim for Intelligent Flight Control," in *An Introduction to Intelligent and Autonomous Control*, P.J. Antsaklis and K.M. Passino, Eds., Kluwer Academic Pub, Boston, MA, pp 371-400, 1993.
- [CAO97] Cao, Y.U., Fukundaga, A.S., and Kahng, A.B., "Cooperative Mobile Robots: Antecedents and Directions," *Autonomous Robots*, Vol. 4, pp. 1-23, Kluwer Academic Pub., Boston, MA, 1997.
- [CCG00] Campbell, K.C., Cooper, W.W., Jr., Greenbaum, D.P., and Wojcik, L.A., "Modeling Distributed Human Decision Making in Traffic Flow Management Operations" *3rd USA/Europe Air Traffic Management R&D Seminar*, Napoli, June, 2000.
- [CEN98] Carr, G.C., Erzberger, H., and Neuman, F., "Delay Exchanges in Arrival Sequencing and Scheduling," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 1657-1667, Aug., 1998.
- [CK91] Conry, S.E., Kuwabara, K., Lesser, V.R., and Meyer, R.A., "Multistage Negotiation for Distributed Constraint Satisfaction," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 21, No. 6, Nov./Dec., 1991.
- [CK92] Chen, F.-C., and Khalil, H.K., "Adaptive Control of Nonlinear Systems using Neural Networks," *Intern. Journal of Control*, Vol. 55, No. 6, pp. 1299-1317, 1992.
- [CL94] Chen, F.-C., and Liu, C.-C., "Adaptively Controlling Nonlinear Continuous-Time Systems using Multilayer Neural Networks," *IEEE Trans. on Automatic Control*, Vol. 39, No. 6, pp. 1306-1310, June, 1994.
- [CMS83] Cammarata, S., McArthur, D., and Steeb, R., "Strategies of Cooperation in Distributed Problem-Solving," *Intern. Joint Conf. on Artificial Intelligence*, Karlsruhe, FRG, pp. 767-770, Aug., 1983.
- [Cr83] Cross, S.E., *Qualitative Reasoning in an Expert System Framework*, Ph.D. Thesis, Dept. of Electrical Engineering, University of Illinois at Urbana-Champaign, Champaign, IL, May, 1983.

- [CRF] Cao, S.G., Rees, N.W., and Feng, G., "Stability Analysis of Fuzzy Control Systems," *IEEE Trans. on Systems, Man, and Cybernetics – Part B: Cybernetics*, Vol. 26, No. 1, pp. 201-204, Feb., 1996.
- [CWC85] Clema, J.K., Werling, R., and Chande, A., "Expert Systems for Real Time Applications," IEEE National Aerospace and Electronics Conf., Dayton, OH, pp. 1322-1329, May, 1985.
- [D90] Dreyfus, S.E., "Artificial Neural Network, Back Propagation, and the Kelley-Bryson Gradient Procedure," *Journal of Guidance, Control, and Dynamics*, Vol. 13, No. 5, pp. 926-928, Sept./Oct., 1990.
- [D97] Dracopoulos, D.C., *Evolutionary Learning Algorithms for Neural Adaptive Control*, Springer-Verlag, New York, NY, 1997.
- [DAC96] Durrand, N., Alliot, J-M, and Chansou, O., "Optimal Resolution of En Route Conflicts," *Air Traffic Control Quarterly*, Vol. 3, No. 3, pp. 139-161, 1996.
- [DAG99] DAG TM Team, Advanced Air Transportation Technologies Program, *Concept Definition for Distributed Air/Ground Traffic Management (DAG TM)*, Version 1.0, NASA Ames Research Center, Sept., 1999.
- [DDMS95] Debelack, A.S., Dehn, J.D., Muchinsky, L.L., and Smith, D.M., "Next Generation Air Traffic Control Automation," *IBM Systems Journal*, Vol. 34, No. 1, pp. 63-77, 1995.
- [DGM97] Duley, J.A., Galster, S.M., Masalonis, A.J., Hilburn, B., and Parasuraman, R., "En Route Controller Information Requirements from Current ATM to Free Flight," *10th CEAS Conf. on Free Flight*, Amsterdam, Oct., 1997.
- [DHJ81] Davies, D.W., Holler, E., Jensen, E.D., Kimbleton, S.R., Lampson, B.W., LeLann, G., Thurber, K.J., and Watson, R.W., *Distributed Systems – Architecture and Implementation*, Springer Verlag, New York, NY, 1981.
- [DP00] Delahaye, D., and Puechmorel, S., "Air Traffic Complexity: Towards Intrinsic Metrics," *3rd USA/Europe Air Traffic Management R&D Seminar*, Napoli, Italy, June, 2000.
- [DS83] Davis, R. and Smith, R.G., "Negotiation as a Metaphor for Distributed Problem Solving," *Artificial Intelligence*, Vol. 20, No. 1, pp. 63-109, 1983.
- [DGP99] Duley, J.A., Galster, S.M., Parasuraman, R., and Smoker, A.J., "En Route ATC Information Requirements for Participation in Future Collaborative Decision Making", *1999 World Aviation Congress*, San Francisco, CA Oct., 1999.
- [Eb94] Eby, M.S., "A Self-Organizational Approach for Resolving Air Traffic Conflicts," *Lincoln Laboratory Journal*, Vol. 7, No. 2, 1994.
- [Eb99] Eby, M.S., and Kelly, W.E., III, "Free Flight Separation Assurance Using Distributed Algorithms," *Proc. of IEEE Aerospace Conf.*, Aspen, CO, March, 1999.
- [E86] Elfes, A., "A Distributed Control Architecture for an Autonomous Mobile Robot," *Artificial Intelligence*, Vol. 1, No. 2, 1986.
- [EM99] Eker, J. and Malmborg, J., "Design and Implementation of a Hybrid Control Strategy," *IEEE Control Systems Magazine*, Vol. 19, No. 4, pp. 12-21, Aug., 1999.
- [EUB97] Evans, K.S., Unsal, C., and Bay, J.S., "A Reactive Coordination Scheme for a Many-Robot System," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 27, No. 4, pp. 598-610, Aug., 1997.
- [FANG97] FMS-ATM Next Generation (FANG) Team, *Airline Operational Control Overview*, U.S. Dept. of Transportation, Federal Aviation Administration, Tech Report DOT/FAA/AND-97/8, July, 1997.
- [FGW89] Fox, G., Gurewitz, E., and Wong, Y-F, "A Neural Network Approach to Multi-Vehicle Navigation," *Intelligent Control and Adaptive Systems*, G. Rodriguez, Ed., SPIE Vol. 1196, Philadelphia, PA, Nov., 1989.
- [FHK98] Fan, T.P., Hyams, D.S., and Kuchar, J.K., "Study of In-Flight Replanning Decision Aids," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 980-988, Aug., 1998.

- [FKL98] Falcone, R., Kollman, K., Leber, B., Moffatt, J., Sandusky, L., Shantz, A., Wambsganss, M., and Wetherly, J., "Demonstrating an Improved Weather Awareness System for CDM," *Journal of ATC*, pp. 50-58, July/Sept., 1998.
- [FHE98] Farley, T.C., Hansman, J., Endsley, M.R., Amonlirdviman, K., and Vigeant-Langlois, L., "The Effect of Shared Information on Pilot/Controller Situation Awareness and Re-Route Negotiation," *2nd USA/Europe Air Traffic Management R&D Seminar*, Orlando, FL, Dec., 1998.
- [FL86] Findler, N.V. and Lo, R., "An Examination of Distributed Planning in the World of Air Traffic Control," *Journal of Parallel and Distributed Computing*, Vol. 3, pp. 411-431, 1986.
- [FWNG98] Fujimori, A., Wu, Z., Nikiforuk, P.N., and Gupta, N.M., "A Design of ALFLEX Flight Control System using Fuzzy Gain-Scheduling," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 1739-1745, Aug., 1998.
- [G88] Ginsberg, A., "Knowledge-Base Reduction: A New Approach to Checking Knowledge-Bases for Inconsistency and Redundancy," *Proc. of the 7th National Conf. on Artificial Intelligence*, St. Paul, MN, pp. 585-589, 1988.
- [GGW97] Green, S., Goka, T., and Williams, D.H., "Enabling User Preferences Through Data Exchange," *AIAA Guidance, Navigation, and Control Conf.*, New Orleans, LA, Aug., 1997.
- [GLS95] Godbole, D.N., Lygeros, J., and Sastry, S., "Hierarchical Hybrid Control: A Case Study," *Hybrid Control II*, Lecture Notes in Computer Science, Vol. 999, pp. 166-190, Springer-Verlag, New York, NY, 1995.
- [GM97] Geng, Z.J. and McCullough, C.L., "Missile Control Using Fuzzy Cerebellar Model Arithmetic Computer Neural Networks," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 3, pp. 557-565, May/June, 1997.
- [GNRR93] Grossman, R.L., Nerode, A., Ravn, A., and Rischel, H., Eds., *Hybrid Systems*, Lecture Notes in Computer Science, Vol. 736, Springer-Verlag, New York, NY, 1993.
- [Gr96] Grosz, B.J., "Collaborative Systems," *AI Magazine*, Vol. 17, No. 2, pp. 67-85, Summer, 1996.
- [GW87] Garvey, T.D. and Wesley, L.P., "Knowledge-Based Helicopter Route-Planning," *Proc. of the DARPA Knowledge-Based Planning Workshop*, Austin, TX, pp. 17-1to 17-10, Dec., 1987.
- [H89] Handelsmann, D.A., *A Rule-Based Paradigm for Intelligent Adaptive Flight Control*, Ph.D. Thesis, Dept. of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, 1989.
- [Ha95] Ha, C.M., "Neural Networks Approach to AIAA Aircraft Control Design Challenge," *Journal of Guidance, Control, and Dynamics*, Vol. 18, No. 4, pp. 731-739, July/Aug., 1995.
- [HH92] How, J.P. and Hall, S.R., "Local Control Design Methodologies for a Hierarchic Control Architecture," *Journal of Guidance, Dynamics, and Control*, Vol. 15, No. 3, pp. 654-663, May-June, 1992.
- [HLM97] Hyemann, M., Lin, F., and Meyer, G., "Viability of Controllers for Hybrid Machines," *Proc. of the 36th IEEE CDC*, San Diego, CA, 1997.
- [HMG99] Harper, K.A., Mulgund, S.S., Guarino, S.L., Mehta, A.B., and Zacharias, G.L., "Air Traffic Controller Agent Model for Free Flight," *AIAA Guidance, Navigation, and Control Conf.*, Portland, OR, Aug., 1999.
- [HS87] Hut, P. and Sussman, G.L., "Advanced Computing for Science," *Scientific American*, Vol. 255, No. 10, 1987.
- [HS89] Handelsmann, D.A., and Stengel, R.F., "Combining Expert System and Analytical Redundancy Concepts for Fault Tolerance Flight Control," *Journal of Guidance, Control, and Dynamics*, Vol. 12, No. 1, pp. 39-45, Jan./Feb., 1989.
- [HvGR96] Hoekstra, J.M., van Gent, R.N., Ruigrok, R.C., "Conceptual Design of Free Flight with Airborne Separation Assurance", *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, p. 807-817, Aug., 1998.
- [HvGR99] Hoekstra, J.M., van Gent, R.N., Ruigrok, R.C., "Designing for Safety: the 'Free Flight' Air Traffic Management Concept", *Human Error, Safety, and System Design Workshop*, Liege, Belgium, 1999.

- [IEEE94] IEEE, Various Authors, *IEEE Expert: Intelligent Systems, and Their Applications*, Issue: "A Fuzzy Logic Symposium", Aug., 1994.
- [IM88] Isik, C. and Meystel, A.M., "Pilot Level of a Hierarchical Controller for an Unmanned Mobile Robot," *IEEE Journal of Robotics and Automation*, Vol. 4, No. 3, pp. 241-255, June, 1988.
- [JF93] Jones, J.L. and Flynn, A.M., *Mobile Robots*, A. K. Peters, Ltd., Wellesley, MA, 1993.
- [JLN99] Jones, R.M., Laird, J.E., Nielsen, P.E., Coulter, K.J., Kenny, P., and Koss, F.V., "Automated Intelligent Pilots for Combat Flight Simulation," *AI Magazine*, Vol. 20, No. 1, pp. 27-41, Spring, 1999.
- [JM95] Jones, P.M., and Mitchell, C.M., "Human-Computer Cooperative Problem Solving: Theory, Design, and Evaluation of an Intelligent Associate System," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 25, No. 7, pp. 1039-1053, July, 1995.
- [JR98] Johansson, M. and Rantzer, A., "Computation of Piecewise Quadratic Lyapunov Functions for Hybrid Systems", *IEEE Trans. on Automatic Control*, Vol. 43, No. 4, April, 1998.
- [JS98] Jacolin, L. and Stengel, R.F., "Evaluation of a Cooperative Air Traffic Management Model using Principled Negotiation between Intelligent Agents," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, Aug., 1998.
- [K87] Key, C., "Cooperative Planning in the Pilot's Associate", *Proc. of the DARPA Knowledge-Based Planning Workshop*, Austin, TX, pp. 13-1 to 13-10, Dec., 1987.
- [Ka97] Kacprzyk, J., *Multistage Fuzzy Control*, J. Wiley and Sons, New York, NY, 1997.
- [KC97] Kim, B.S. and Calise, A.J., "Nonlinear Flight Control Using Neural Networks," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 1, pp. 26-33, Jan./Feb., 1997.
- [Kl00] Klarreich, E.G., "Foams and Honeycombs," *American Scientist*, Vol. 88, pp. 152-161, March/April, 2000.
- [KGSZ95] KrishnaKumar, K., Gonsalves, P., Satyadas, A., and Zacharias, G., "Hybrid Fuzzy Logic Flight Controller Synthesis via Pilot Modeling," *Journal of Guidance, Control, and Dynamics*, Vol. 18, No. 5, pp. 1098-1105, Sept./Oct., 1995.
- [KH95] Kuchar, J.K., and Hansman, R.J. Jr., *A Unified Methodology for the Evaluation of Hazard Alerting Systems*, Tech. Report ASL-95-1, Aeronautical Systems Laboratory, M.I.T., Cambridge, MA, Jan., 1995.
- [KMD92] Kraft, L.G., Miller, W.T., and Dietz, D., "Development and Application of CMAC Neural Network-Based Control," in *Handbook of Intelligent Control*, D. A. White and D.A. Sofge, (Eds.), Von Nostrand Reinhold, New York, NY, pp. 215-232, 1992.
- [KMH96] Krozel, J., Mueller, T., and Hunter, G., "Free Flight Conflict Detection and Resolution Analysis," *AIAA Guidance, Navigation, and Control Conf.*, San Diego, CA, July, 1996.
- [Kn93] Knapp, R.G., *Fuzzy Based Attitude Controller for Flexible Spacecraft with On/Off Thrusters*, M.S. Thesis, Dept. of Aeronautics and Astronautics, MIT, Cambridge, MA, May, 1993.
- [KP97a] Krozel, J. and Peters, M. "Conflict Detection and Resolution for Free Flight", *Air Traffic Control Quarterly*, Vol. 5, No. 3, pp. 181-212, 1997.
- [KP97b] Krozel, J. and Peters, M. "Strategic Conflict Detection and Resolution for Free Flight", *IEEE Conf. on Decision and Control*, San Diego, CA, Dec., 1997.
- [KPB00] Krozel, J., Peters, M., and Bilimoria, K., "A Decentralized Control Strategy for Distributed Air/Ground Traffic Separation," *AIAA Guidance, Navigation, and Control Conf.*, Denver, CO, Aug., 2000.
- [KRM97] Kohn, W., Rummel, J.B., Moser, W.R., and Cummings, B., "Free Flight ATC using Hybrid Agent Systems", *Proc. of the 36th IEEE CDC*, San Diego, CA, Dec., 1997.
- [KrS99] Krozel, J., and Schleicher, D., "An Airspace Visualization Tool for Collaborative Decision Making", *10th Intern. Symposium on Aviation Psychology*, Columbus, OH, May, 1999.

- [KSD99] Krozel, J., Schleicher, D., and Dow, D., "Collaborative Decision Making Airspace Visualization Tool", *AIAA Modeling and Simulation Technologies Conf.*, Portland, OR, Aug., 1999.
- [Ku96] Kuchar, J.K., "Methodology for Alerting-System Performance Evaluation," *Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 2, pp. 438-444, March/April, 1996.
- [KV96] Kourjanski, M. and Varaiya, P., "Stability of Hybrid Systems," *Hybrid Systems III*, Lecture Notes in Computer Science, Vol. 1066, Springer-Verlag, New York, NY, 1996.
- [KY97] Kuchar, J.K. and Yang, L.C., "Survey of Conflict Detection and Resolution Modeling Methods," *AIAA Guidance, Navigation, and Control Conf.*, New Orleans, LA, pp. 1388-1397, Aug., 1997.
- [KuS99] Kuwata, Y., and Sugimoto, T., "Intelligent Techniques in Air Traffic Management," in *Intelligent Adaptive Control*, Jain, L.C. and deSilva, C.W., Eds., CRC Press, New York, NY, 1999.
- [L79] Larson, R.E., "A Survey of Distributed Control Techniques," in *Distributed Control*, IEEE Computer Society, New York, NY, 1979.
- [L84] Larkin, L.I., "A Fuzzy Logic Controller for Aircraft Flight Control," *IEEE Decision and Control Conf.*, Las Vegas, NV, pp. 894-897, Dec., 1984.
- [L85] Larkin, L.I., "A Fuzzy Logic Controller for Aircraft Flight Control," *Industrial Applications of Fuzzy Control*, M. Segeno (Ed.), Elsevier Science Pub., pp. 87-103, 1985.
- [L86] Lukas, M.P., *Distributed Control Systems*, Von Nostrand Reinhold Comp., New York, NY, 1986.
- [L87] Loch, J.L., *Design of a Reflexive Hierarchical Control System for an Autonomous Underwater Vehicle*, M.S. Thesis, Dept. of Aeronautics and Astronautics, M.I.T., June, 1989.
- [L90a] Lee, C.C., "Fuzzy Logic in Control Systems: Fuzzy Logic Controller – Part I", *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 20, No. 2, pp. 404-418, March/April, 1990.
- [L90b] Lee, C.C., "Fuzzy Logic in Control Systems: Fuzzy Logic Controller – Part II", *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 20, No. 2, pp. 419-435, March/April, 1990.
- [L98] Lesser, V.R., "Reflections on the Nature of Multi-Agent Coordination and Its Implications for an Agent Architecture," *Autonomous Agents and Multi-Agent Systems*, Kluwer Academic Pub., Vol. 1, pp. 89-111, July, 1998.
- [LB92] Langari, R. and Berenji, H.R., "Fuzzy Logic in Control Engineering," in *Handbook of Intelligent Control: Neural, Fuzzy, and Adaptive Approaches*, D.A. White and D.A. Sofge, (Eds.), Van Nostrand Reinhold, New York, NY, 1992.
- [LC81] Lesser, V. R. and Corkill, D.D., "Functionally Accurate, Cooperative Distributed Systems," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. SMC-11, No. 1, pp. 81-96, 1981.
- [LCP97] Leitner, J., Calise, A., and Prasad, J.V.R., "Analysis of Adaptive Neural Networks for Helicopter Flight Control," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 5, pp. 972-979, Sept./Oct., 1997.
- [LCS88] Laffey, T.J., Cox, P.A., Schmidt, J.L., Kao, S.M., and Read, J.Y., "Real-Time Knowledge-Based Systems," *AI Magazine*, Vol. 9, No. 1, pp. 27-45, Spring, 1988.
- [LJY99] Lewis, F.L., Jagannathan, S., and Yesildirek, A., *Neural Network Control of Robot Manipulators and Nonlinear Systems*, Taylor and Francis, Philadelphia, PA, 1999.
- [LM97] Lin, C.-M. and Maa, J.-H., "Flight Control System Design by Self-Organizing Fuzzy Logic Controller," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 1, pp. 189-190, Jan./Feb., 1997.
- [LP95] Lunardi A.D., and Passino, K.M., "Verification of Qualitative Properties of Rule-Based Expert Systems", *Intern. Journal of Applied Artificial Intelligence*, Vol. 9, No. 6, pp. 587-621, Nov./Dec. 1995.

- [LS96] Lewis, L. F., and Spich, R.S., "Principled Negotiation, Evolutionary Systems Design, and Group Support Systems: A Suggested Integration of Three Approaches to Improving Negotiations," *Proc. of the 29th Annual Hawaii Intern. Conf. on System Sciences*, 1996.
- [LSBB98] Laudeman, I.V., Shelden, S.G., Branstrom, R., and Brasil, C.L., *Dynamic Density: An Air Traffic Management Metric*, Technical Memorandum TM-1998-112226, NASA Ames Research Center, Moffett Field, CA, April, 1998.
- [LT90] Langari, G. and Tomizuka, M., "Stability of Fuzzy Linguistic Control Systems," *Proc. of the 29th Conf. on Decision and Control*, Honolulu, HI, pp. 2185-2190, Dec., 1990.
- [LTD97] Li, K-W, Turksen, I.B., Davison, E. J., and Smith, K. C., "Stabilization of Unstable and Unintuitive Plants by Fuzzy Control", *IEEE Trans. on Systems, Man, and Cybernetics – Part B: Cybernetics*, Vol. 27, No. 1, pp. 55-67, Feb., 1997.
- [M74] Mamdani, E.H., "Applications of Fuzzy Algorithms for Control of Simple Dynamic Plant", *Proc. of IEE*, Vol. 121, No. 12, pp 1585-1588, 1974.
- [Me98] Meckiff, C., "Conflict Resolution Support for Random Routing," *Air Traffic Control Quarterly*, Vol. 6, No. 2, pp. 87-118, 1998.
- [MSS97] Menon, P.K., Sweriduk, G.D., and Sridhar, B., "Optimal Strategies for Free Flight Air Traffic Conflict Resolution," *AIAA Guidance, Navigation, and Control Conf.*, New Orleans, LA, pp. 455-468, Aug., 1997.
- [M87] Meystel, A., "Theoretical Foundations of Planning and Navigation for Autonomous Robots," *Intern. Journal of Intelligent Systems*, Ronald R. Yager, Ed., Vol. 2, No. 2, pp. 73-128, Summer, 1987.
- [M93] Meystel, A., "Nested Hierarchical Control," in *An Introduction to Intelligent and Autonomous Control*, P.J. Antsaklis and K.M. Passino, Eds., Kluwer Academic Pub, Boston, MA, pp 129-161, 1993.
- [M99] Mueller, K.T., "Statistical Performance Analysis Simulation of the FAST Merging Procedure Fuzzy Logic," *AIAA Guidance, Navigation, and Control Conf.*, Portland, OR, Aug., 1999.
- [Mae92] Maes, P., "Behavior-Based Artificial Intelligence," *Proc. of the 2nd Intern. Conf. on Simulation of Adaptive Behavior*, MIT Press, 1992.
- [Mat92] Mataric, M., "Minimizing Complexity in Controlling a Mobile Robot Population," *IEEE Intern. Conf. on Robotics and Automation*, Nice, FR, May, 1992.
- [MD90] McIngvale, P.H. and Dudley, S.E., "Expert System Technology Applied to the Automatic Control of Multiple Unmanned Aerial Vehicles," *AIAA/AHS/ASAE Aircraft Design, Systems and Operations Conf.*, Dayton, OH, Sept., 1990.
- [MG90] McManus, J.W. and Goodrich, K.H., "Artificial Intelligence (AI) Based Tactical Guidance for Fighter Aircraft," *AIAA Guidance, Navigation, and Control Conf.*, Portland, OR, Aug., 1990.
- [MGMK95] Mogford, R.H., Guttman, J.A., Morrow, S.L., and Kopardekar, P., *The Complexity Construct in Air Traffic Control: A Review and Synthesis of the Literature*, Tech. Report DOT/FAA/CT-TN95/22, US Dept. of Transportation, Federal Aviation Administration, Atlantic City, NJ, July, 1995.
- [MMG94] Mogford, R.H., Murphy, E.D., and Guttman, J.A., "Using Knowledge Exploration Tools to Study Airspace Complexity in Air Traffic Control," *Intern. Journal of Aviation Psychology*, Vol. 4, No. 1, pp. 29-45, 1994.
- [MR98] Mueller, K.T. and Robinson, J.E., III, "Final Approach Spacing Tool (FAST) Velocity Accuracy Performance Analysis," *AIAA Guidance, Navigation, and Control Conf.*, MA, pp. 1711-1721, Aug., 1998.
- [N92] Narendra, K.S., "Adaptive Control of Dynamical Systems using Neural Networks," in *Handbook of Intelligent Control*, D. A. White and D.A. Sofge, (Eds.), Von Nostrand Reinhold, New York, NY, pp. 141-183, 1992.
- [N94] Neuman, B.C., "Scale in Distributed Systems," in *Readings in Distributed Computing Systems*, IEEE Computer Society Press, 1994.

- [N98] Niedringhaus, W.P., "Solution Complexity Measure," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 30-51, Aug., 1998.
- [NA98] Nho, K., and Agarwal, R.K., "Automatic Landing System Design Using Fuzzy Logic", *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 1729-1738, Aug., 1998.
- [NK95] Napolitano, M.R. and Kincheloe, M., "On-Line Learning Neural-Network Controllers for Autopilot Systems," *Journal of Guidance, Control, and Dynamics*, Vol. 33, No. 6, pp. 1008-1015, Nov./Dec., 1995.
- [NNNC95] Napolitano, M.R., Naylor, S., Neppach, C., and Casdorph, V., "On-Line Learning Nonlinear Direct Neurocontrollers for Restructurable Control Systems," *Journal of Guidance, Control, and Dynamics*, Vol. 18, No. 1, pp. 170-176, Jan./Feb., 1995.
- [NPLP85] Nguyen, T.A., Perkins, W.A., Laffey, T.J., and Pecora, D., "Checking an Expert Systems Knowledge Base for Consistency and Completeness," *Proc. of the Ninth Intern. Joint Conf. on Artificial Intelligence*, Los Angeles, CA, pp. 375-378, Aug., 1985.
- [NPLP87] Nguyen, T.A., Perkins, W.A., Laffey, T.J., and Pecora, D., "Knowledge-Base Verification," *AI Magazine*, Vol. 8, No. 2, pp. 69-75, Summer, 1987.
- [O95] Onken, R., "Functional Development and Field Test of CASSY – A Knowledge-Based Cockpit Assistant System," *AGARD Lecture Series 200: Knowledge-Based Functions in Aerospace Systems*, presented at NASA Ames Research Center, Moffett Field, CA, Nov., 1995.
- [P98] Paielli, R.A., "Empirical Test of Conflict Probability Estimation", *2nd USA/Europe Air Traffic Management R&D Seminar*, Orlando, FL, Dec., 1998.
- [PE97] Paielli, R.A., and Erzberger, H., "Conflict Probability Estimation for Free Flight," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 3, pp. 588-596, May-June, 1997.
- [PE99] Paielli, R.A., and Erzberger, H., "Conflict Probability Estimation Generalized to Non-Level Flight", *Air Traffic Control Quarterly*, Vol. 7, No. 3, pp. 195-222, 1999.
- [P90] Payton, D.W., "Internalized Plans: A Representation for Action Resources," *Robotics and Autonomous Systems*, Vol. 6, pp. 89-103, 1990.
- [P92] Parker, L.E., *Local versus Global Control Laws for Cooperative Agent Teams*, M.I.T. Artificial Intelligence Laboratory, A.I. Memo No. 1357, Cambridge, MA, March, 1992.
- [P94] Parker, L.E., *Heterogeneous Multi-Robot Cooperation*, Ph.D. Thesis, Dept. of Electrical Engineering and Computer Science, M.I.T., Feb., 1994.
- [P98] Parker, L.E., "ALLIANCE: An Architecture for Fault Tolerant Multi-Robot Cooperation," *IEEE Trans. on Robotics and Automation*, Vol. 14, No. 2, pp. 220-240, April, 1998.
- [PB91] Payton, D.W., and Bihari, T.E., "Intelligent Real-Time Control of Robotic Vehicles," *Comm. of the ACM*, Vol. 34, No. 8, pp. 49-63, Aug., 1991.
- [PB96] Pawlak, W.S., Brinton C.R., Crouch, K., and Lancaster, K.M., "A Framework for Evaluation of Air Traffic Control Complexity," *AIAA Guidance, Navigation, and Control Conf.*, San Diego, CA, July, 1996.
- [PJ84] Pisano, A.D., and Jones, H.L., "An Expert Systems Approach to Adaptive Tactical Navigation," *Proc. of the First Conf. on Artificial Intelligence Applications*, Washington, DC, pp. 460-464, 1984.
- [PKK92] Payton, D.W., Keirsey, D., Kimble, D.M., Krozel, J., and Rosenblatt, J.K., "Do Whatever Works: A Robust Approach to Fault-Tolerant Autonomous Control," *Journal of Applied Intelligence*, Vol. 2, pp. 225-250, 1992.
- [PL93] Passino, K.M., and Lunardhi, A.D., "Stability Analysis of Expert Control Systems," *IEEE Control and Decision Conf.*, pp. 765-770, 1993.
- [PL96] Passino K.M. and Lunardhi, A.D., "Qualitative Analysis of Expert Control Systems", in Gupta M.M., Sinha N.K., eds., *Intelligent Control: Theory and Applications*, pp. 404-442, IEEE Press, Piscataway, NJ, 1996.

- [PRK90] Payton, D.W., Rosenblatt, J.K., and Keirsey, D.M., "Plan Guided Reaction," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 20, No. 6, pp. 1370-1382, Nov./Dec., 1990.
- [PS90] Pradeep, S. and Shrivastava, S.K., "Stability of Dynamical Systems: An Overview", *Journal of Guidance, Control, and Dynamics*, Vol. 13, No. 3, pp. 385-393, May/June, 1990.
- [PSB92] Preece, A.D., Shinghal, R., and Batarekh, A., "Principles and Practice in Verifying Rule-Based Systems," *Knowledge Engineering Review*, Vol. 7, No. 2, pp. 115-141, 1992.
- [PTS96] Pappas, G.J., Tomlin, C., and Sastry, S., "Conflict Resolution for Multi-Agent Hybrid Systems", *Proc. of the 35th IEEE CDC*, pp. 1184-1189, Dec., 1996.
- [QZ98] Quinn, C. and Zelenka, R.E., "ATC/Air Carrier Collaborative Arrival Planning," *2nd USA/Europe Air Traffic Management R&D Seminar*, Orlando, FL, Dec., 1998.
- [R94] Resnick, M., *Turtles, Termites, and Traffic Jams*, MIT Press, Cambridge, MA, 1994.
- [R99] Reilly, C., "Collaboration: Developing a Global Information Exchange", *Proc. of the 44th Air Traffic Controller's Assoc. Conf.*, pp. 113-117, San Diego, CA, Sept., 1999.
- [RC94] Rovithakis, G.A., and Christodoulou, M.A., "Adaptive Control of Unknown Plants using Dynamical Neural Networks," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 24, No. 3, pp. 400-412, 1994.
- [RC98] Rysdyk, R.T., and Calise, A.J., "Fault Tolerant Flight Control via Adaptive Neural Network Augmentation," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 1722-1728, Aug., 1998.
- [RDI97] Robinson, J.E., Davis, T.J., and Isaacson, D.R., "Fuzzy Reasoning-Based Sequencing of Arrival Aircraft in the Terminal Area," *AIAA Guidance, Navigation, and Control Conf.*, New Orleans, LA, Aug., 1997.
- [RG85] Rosenchein, J.S., and Genesereth, M.R., "Deals Among Rational Agents", *Proc. of the 9th Intern. Joint Conf. on Artificial Intelligence*, Los Angeles, CA, pp. 91-99, Aug., 1985.
- [RJM88] Rubin, K.S., Jones, P.M., and Mitchell, C.M., "OFMspert: Inference of Operator Intentions in Supervisory Control using a Blackboard Architecture," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 18, No. 4, pp. 618-637, July/Aug., 1988.
- [RM84] Ray, K.S. and Majumder, D.D., "Application of Circle Criteria for Stability Analysis of Linear SISO and MIMO Systems Associated with Fuzzy Logic Controller," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. SMC-14, No. 2, pp. 345-349, March/April, 1984.
- [RMM97] Rodgers, M.D., Mogford, R.H., and Mogford, L.S., "The Relationship of Sector Characteristics to Operational Errors," *Air Traffic Control Quarterly*, Vol. 5, No. 4, pp. 241-263, 1997.
- [RS93] Rokhsaz, K. and Steck, J.E., "Use of Neural Networks in Control of High-Alpha Maneuvers," *Journal of Guidance, Control, and Dynamics*, Vol. 16, No. 5, pp. 934-939, Sept./Oct., 1993.
- [RS99] Rock, D., and Sullivan, E.J., "Negotiation Automation for Special Use Airspace," *AIAA Guidance, Navigation, and Control Conf.*, Portland, OR, pp. 335-344, Aug., 1999.
- [RTCA95] Radio Technical Commission for Aeronautics, *Report of the RTCA Board of Directors' Select Committee on Free Flight*, RTCA, Inc., Washington, DC, Jan., 1995.
- [RV99] Rufus, F., and Vachtsevanos, G., "Robust Stability of Mode-to-Mode Fuzzy Controllers," *Journal of Guidance, Control, and Dynamics*, Vol. 22, No. 6, pp. 823-832, Nov./Dec., 1999.
- [RZ94a] Rosenschein, J.S. and Zlotkin, G., *Rules of Encounter*, MIT Press, Cambridge, MA, 1994.
- [RZ94b] Rosenschein, J.S. and Zlotkin, G., "Designing Conventions for Automated Negotiation," *AI Magazine*, Vol. 15, No. 3, pp. 29-46, Fall, 1994.
- [S85] Sugeno, M., "An Introductory Survey of Fuzzy Control," *Information Sciences*, Vol. 36, pp. 59-83, 1985.
- [S93] Stengel, R.F., "Towards Intelligent Flight Control," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 23, No. 6, pp. 1699-1717, Nov./Dec., 1993.

- [S98] Sycara, K.P., "Multiagent Systems," *AI Magazine*, Vol. 19, No. 2, pp. 79-92, Summer, 1998.
- [Sa91] Sanner, R.B., and Slotine, J.-J.E., "Stable Adaptive Control and Recursive Identification using Radial Gaussian Networks," *Proc. of the IEEE Conf. on Decision and Control*, Brighton, MA, 1991.
- [Sa93] Sadegh, N., "A Perceptron Network for Functional Identification and Control of Nonlinear Systems," *IEEE Trans. on Neural Networks*, Vol. 4, No. 6, pp. 982-988, Nov., 1993.
- [SSG98] Sridhar, B., Sheth, K.S., and Grabbe, S., "Airspace Complexity and its Application in Air Traffic Management," *2nd USA/Europe Air Traffic Management R&D Seminar*, Orlando, FL, Dec., 1998.
- [SCH88] Steeb, R., Cammarata, S., Hayes-Roth, F.A., Thorndyke, P.W., and Wesson, R.B., "Distributed Intelligence for Air Fleet Control," *Readings in Distributed Artificial Intelligence*, A.H. Bond and L. Gasser (Eds), Morgan Kaufmann Pub., Inc., pp. 90-101, 1988.
- [SCH88] Steeb, R., Cammarata, S., Hayes-Roth, F.A., Thorndyke, P.W., and Wesson, R.B., "Distributed Intelligence for Air Fleet Control," *Readings in Distributed Artificial Intelligence*, A.H. Bond and L. Gasser (Eds), Morgan Kaufmann Pub., Inc., pp. 90-101, 1988.
- [SD81] Smith, R.G., and Davis, R., "Frameworks for Cooperation in Distributed Problem Solving," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 11, No. 1, pp. 61-70, 1981.
- [SH89] Skillman, T.L. and Hopping, K., "Dynamic Composition and Execution of Behaviors in a Hierarchical Control System," *SPIE Mobile Robots IV*, Philadelphia, PN, Nov., 1989.
- [SK88] Skillman, T., Kohn, W., and Graham, R., "Hierarchical Control of a Mobile Robot with a Blackboard Based System," *Mobile Robots III*, W. J. Wolfe, Ed., Proc. SPIE Vol. 1007, pp. 256-262, Nov., 1988.
- [SK90] Skillman, T.L., Kohn, W., Nguyen, D., Ling, C., and Dodhiawala, R., "Class of Hierarchical Controllers and Their Blackboard Implementations," *Journal of Guidance, Control, and Dynamics*, Vol. 13, No. 1, pp. 176-182, Jan./Feb., 1990.
- [SM97] Stothert, A., and MacLeod, I.M., "Distributed Intelligent Control System for a Continuous-State Plant," *IEEE Trans. on Systems, Man, and Cybernetics – Part B: Cybernetics*, Vol. 27, No. 1, pp. 395-401, June, 1997.
- [SML97] Smith, P.J., McCoy, C.E., and Layton, C., "Brittleness in the Design of Cooperative Problem-Solving Systems: The Effects of User Performance", *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 27, No. 3, pp. 360-371, May, 1997.
- [SMO97] Smith, P.J., McCoy, E., Orasanu, J., et al, "Control by Permission: A Case Study of Cooperative Problem Solving in the Interactions of Airline Dispatchers with ATCSCC," *Air Traffic Control Quarterly*, Vol. 4, No. 4, pp. 229-247, 1997.
- [SMT95] Sastry, S., Meyer, G., Tomlin, C., Lygeros, J., Godbole, D., and Pappas, G., "Hybrid Control in Air Traffic Management Systems," *Proc. of the 34th IEEE Conf. in Decision and Control*, New Orleans, LA, Dec., 1995
- [SMT95] Sastry, S., Meyer, G., Tomlin, C., Lygeros, J., Godbole, D., and Pappas, G., "Hybrid Control in Air Traffic Management Systems," *Proc. of the 34th IEEE Conf. in Decision and Control*, New Orleans, LA, Dec., 1995
- [SSKH98] Smith, K., Scallen, S.F., Knecht, W., and Hancock, P.A., "An Index of Dynamic Density," *Journal of the Human Factors and Ergonomics Society*, Vol. 40, No. 1, pp. 69-78, March, 1998.
- [SSS82] Suwa, M., Scott, A.C., and Shortliffe, E.H., "An Approach to Verifying Completeness and Consistency in a Rule-Based Expert System," *AI Magazine*, Vol. 3, No. 4, pp. 16-21, Fall, 1982.
- [St93] Steinberg, M., "Development and Simulation of an F/A-18 Fuzzy Logic Automatic Carrier Landing System," *2nd IEEE Intern. Conf. on Fuzzy Systems*, San Francisco, CA, pp. 797-802, March/April, 1993.
- [SW93] Stengel, R.F. and Wangermann, J.P., "Air Traffic Management as Principled Negotiation between Intelligent Agents," *AGARD Meeting on Machine Intelligence in ATM.*, Berlin, Germany, May, 1993.

- [SW98] Sasiadek, J.Z. and Wang, Q., "3-D Guidance and Navigation of Mobile and Flying Robot Using Fuzzy Logic," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 235-243, Aug., 1998.
- [SWN98] Smith, D.W., Ward, D.T., and Nguyen, T.X., "An Improved Artificial Neural Network Flight Mode Interpreter," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 438-448, Aug., 1998.
- [Ta99] Takai, S., "Minimizing the Set of Local Supervisors in Fully Decentralized Supervision," *IEEE Trans. on Automatic Control*, Vol. 44, No. 7, pp. 1441-1444, July, 1999.
- [TBCJ93] Turner, R.M., Blidberg, D.R., Chappell, S.G., and Jalbert, J.C., "Generic Behaviors: An Approach to Modularity in Intelligent Systems Control," *Proc. of the 8th Intern. Symposium on Unmanned Untethered Submersible Technology*, Durham, NH, 1993.
- [TED94] Turner, R.M., Eaton, P.S., and Dempsey, M.J., "Handling Unanticipated Events in Single and Multiple AUV Systems," *Proc. of Conf. of the IEEE Oceanic Engineering Society (OCEANS)*, Brest, FR, pp.125-130, 1994.
- [TGM93] Troudet, T., Garg, S., and Merrill, W., "Neurocontrol Design and Analysis for a Multivariable Aircraft Control Problem," *Journal of Guidance, Control, and Dynamics*, Vol. 16, No. 4, pp. 738-747, July/Aug., 1993.
- [To77] Tong, R. M., "A Control Engineering Review of Fuzzy Systems," *Automatica*, Vol. 13, pp. 559-569, Pergamon Press, 1977.
- [To85] Tong, R.M., "An Annotated Bibliography of Fuzzy Control," *Industrial Applications of Fuzzy Control*, M. Segeno, (Ed.), Elsevier Science Pub., 1985.
- [TPS98] Tomlin, C., Pappas, G.J., and Sastry, S., "Conflict Resolution for Air Traffic Management: A Study in Multiagent Hybrid Systems," *IEEE Trans. on Automatic Control*, Vol. 43, No. 4, pp. 509-521, April, 1998.
- [TS77] Teneketzis, D. and Sandell, N.R., "Linear Regulator Design for Stochastic Systems by a Multiple Time-Scales Method," *IEEE Trans. on Automated Control*, Aug., 1977.
- [TS81] Tenney, R.R. and Sandell, Jr., N.R., "Strategies for Distributed Decisionmaking," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. SMC-11, No. 8, pp. 527-538, 1981.
- [Tu93] Turner, R.M., "Context-Sensitive Reasoning for Autonomous Agents and Cooperative Distributed Problem Solving," *Proc. of the 1993 IJCAI Workshop on Using Knowledge in Its Context*, Chambéry, France, 1993.
- [Tu98] Turner, R.M., "Context- Mediated Behavior for Intelligent Agents", *Intern. Journal of Human-Computer Studies*, Special issue on Using Context in Applications, Vol. 48, No. 3, pp. 307-330, March, 1998.
- [Ty89] Tynor, S.D., "Reflexive Navigation for Autonomous Aircraft," *AIAA Computers in Aerospace VII Conf.*, Monterey, CA, pp. 218-224, Oct, 1989.
- [Ty93] Tyrrell, T., "The Use of Hierarchies for Action Selection," *Adaptive Behavior Journal*, Vol. 1, No. 4, pp. 387-420, 1993.
- [UFA92] Ueyama, T., Fukuda, T., and Ahai, F., "Configuration of Communication Structure for Distributed Intelligent Robotic System," *IEEE Intern. Conf. on Robotics and Automation*, Nice, FR, pp. 807-812, May, 1992.
- [W92] Werbos, P.J., "Neurocontrol and Supervised Learning: An Overview and Evaluation," in *Handbook of Intelligent Control*, D. A. White and D.A. Sofge, (Eds.), Von Nostrand Reinhold, New York, NY, pp. 65-89, 1992.
- [Wa97] Wambsganss, M., "Collaborative Decision Making Through Dynamic Information Transfer," *Air Traffic Control Quarterly*, Vol. 4, No. 2, pp. 109-125 , 1997.
- [Wi97] Williams, G.P., *Chaos Theory Tamed*, Joseph Henry Press, Washington, DC, 1997.
- [WS94] Wangermann, J.P. and Stengel, R.F., "Principled Negotiation between Intelligent Agents: A model for Air Traffic Management," *19th ICAS Congress*, Anaheim, CA, Sept., 1994.

- [WS96a] Wangermann, J.P. and Stengel, R.F., "Optimization and Coordination of Multi-Agent Systems Using Principled Negotiation," *AIAA Guidance, Navigation, and Control Conf.*, San Diego, CA, July, 1996.
- [WS96b] Wangermann, J.P. and Stengel, R.F., "Distributed Optimization and Principled Negotiation for Advanced Air Traffic Management," *Proc. of the 1996 IEEE Intern. Symposium on Intelligent Control*, Dearborn, MI, Sept., 1996.
- [WS99] Wangermann, J.P. and Stengel, R.F., "Optimization and Coordination of Multiagent Systems Using Principled Negotiation," *Journal of Guidance, Control, and Dynamics*, Vol. 22, No. 1, pp. 43-50, Jan./Feb., 1999.
- [WSK86] Weisbin, C.R., de Saussure, G., and Kammer, D.W., "A Real-Time Expert System for Control of an Autonomous Mobile Robot Including Diagnosis of Unepected Occurrences," *SPIE Vol. 729 Space Station Automation II*, Cambridge, MA, pp. 49-58, Oct., 1986.
- [YK98] Yang, L., and Kuchar, J., "Using Intent Information in Probabilistic Conflict Analysis," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, Aug., 1998.
- [YMH98] Ye, H., Michel, A.N., and Hou, L., "Stability Theory for Hybrid Dynamical Systems," *IEEE Trans. on Automatic Control*, Vol. 43, No. 4, pp. 461-474, April, 1998.
- [YNS86] Yoerlger, D.R., Newman, J.B., and Slotine, J-J E., "Supervisory Control System for the JASON ROV," *IEEE Journal of Oceanic Engineering*, Vol. OE-11, No. 3, pp. 392-400, July, 1986.
- [Z73] Zadeh, L.A., "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. SMC-3, No. 1, pp. 28-44, Jan., 1973.
- [Ze98] Zeghal, K., "A Review of Different Approaches Based on Force Fields for Airborne Conflict Resolution," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 818--827, Aug., 1998.
- [ZBE98] Zelenk, R.E., Beatty, R., and Engelland, S., "Preliminary Results of the Impact of CTAS Information on Airline Operational Control," *AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, pp. 1698-1710, Aug., 1998.
- [ZR91] Zlotkin, G., and Rosenschein, J.S., "Cooperation and Conflict Resolution via Negotiation Among Autonomous Agents in Non-cooperative Domains," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 21, No. 6, Nov./Dec., 1991.
- [ZR96] Zlotkin, G., and Rosenschein, J.S., "Mechanisms for Automated Negotiation in State Oriented Domains," *Journal of Artificial Intelligence Research*, Vol. 5, pp. 163-238, 1996.